FOURTH

NASA INTERCENTER CONFERENCE ON PLASMA PHYSICS

IN

WASHINGTON D.C.

2–4 DECEMBER 1963

SPONSORED BY FLUID PHYSICS BRANCH
OFFICE OF ADVANCED RESEARCH AND TECHNOLOGY
NASA HEADQUARTERS

PROGRAM MANAGEMENT AND CONTACT K. THOM, CODE: RRP

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546

LIST OF PRESENTATIONS
FOURTH NASA INTERCENTER CONFERENCE
ON PLASMA PHYSICS

Monday Morning, 2 Dec. 1963 — 8:30 a.m.

Welcome Address — H. H. Kurzweg, Director of Research
NASA Headquarters, Washington, D. C.

Introductory Remarks — K. Thom, NASA Hqs., Washington, D. C.

SESSION I: Plasma Theory and Plasma Generation
Chairman: E. Reshotko, NASA Lewis Research Center,
Cleveland, Ohio

1. Theory of Low Density Plasmas
D. A. Tidman
University of Maryland, College Park, Maryland

2. Studies of Pair-Correlations in Plasma Theory
C. S. Wu, E. H. Klevans, J. S. Zmuidzinas
Jet Propulsion Laboratory, Pasadena, California

3. Reentry Heat Transfer and Plasma Statistics
W. E. Meador
NASA Langley Research Center, Hampton, Virginia

4. MHD Problems Related to the Interplanetary Magnetic Field
D. Adamson
NASA Langley Research Center, Hampton, Virginia

5. Theory of Solar Wind - Geomagnetic Field Interaction
C. C. Chang, Catholic University, Washington, D. C.

6. Experimental Study of Discharge at Neutral Point
A. Bratenahl
Jet Propulsion Laboratory, Pasadena, California

(BREAK)

7. Three Body Collisional Recombination of Cesium Ions and Electrons in an Optically Thin Plasma
J. V. Dugan, Jr.
NASA, Lewis Research Center, Cleveland, Ohio

8. The Afterglow Technique in Plasma Research
E. H. Holt, R. E. Haskell, J. S. Mendell
Rensselear Polytechnic Institute, Troy, New York

9. Electron Collision Phenomena in Nitrogen
K. C. Stotz
Rensselear Polytechnic Institute, Troy, New York

10. Volume Ion Production Cost and Spectroscopic Diagnostics in a Helium Plasma
R. J. Sovie
NASA Lewis Research Center, Cleveland, Ohio

11. Electron Beam Mode Discharge Studies
J. Litton, Jr.
Martin Company, Baltimore, Maryland

12. Electric Drag of Charged Spheres
W. C. Pitts and E. D. Knechtel
NASA, Ames Research Center, Mountain View, California

Monday Afternoon, 2 Dec. 1963 2:00 p.m.

SESSION II: Dynamics of Pulsed Plasmas
Chairman: I. Schwartz, NASA Headquarters, Washington, D. C.

1. The Use of a Transmission-Line Energy-Source with a Coaxial Plasma Gun
T. J. Gooding, B. R. Hayworth, A. V. Larson
General Dynamics Astronautics, San Diego, California

2. Performance Study of a Repetitively Pulsed Two-Stage Plasma Propulsion Engine
B. Gorowitz, P. Gloersen, J. H. Rowe
General Electric Company, King of Prussia, Pennsylvania

3. Operating and Exhaust Characteristics of a Coaxial Plasma Gun
C. J. Michels
NASA Lewis Research Center, Cleveland, Ohio

4. Spectroscopic Observations on a Pulsed Coaxial Plasma Gun and Radiation Losses from Plasmas Consisting of High Z-Materials
G. Oertel, N. Jalufka, J. Norwood
NASA Langley Research Center, Hampton, Virginia

(BREAK)

5. Radiation from High Temperature Plasmas
A. C. Kolb
U. S. Naval Research Laboratory, Washington, D. C.

6. Spectral Line Intensities Emitted by Optically Thin Plasmas
G. Oertel, M. T. Raiford
NASA, Langley Research Center, Hampton, Virginia

7. Magnetic Compression Experiment
G. Oertel
NASA Langley Research Center, Hampton, Virginia

8. Pulsed Electromagnetic Gas Acceleration
   R. G. Jahn, W. von Jaskowsky
   Princeton University, Princeton, New Jersey

9. Measurements of High Energy Plasmas in Under-Water Spark Channels at 10^5 Atmospheres
   J. W. Robinson, H. C. Early
   The University of Michigan, Ann Arbor, Michigan

Tuesday Morning, 3 Dec. 1963 — 9:00 a.m.

SESSION III: DC-Plasma Acceleration and Heating
Chairman: G. P. Wood, NASA Langley Research Center

1. The Shape of an Electric Arc in an Annular Gap and an Axial Magnetic Field
   J. R. Jedlicka
   NASA Ames Research Center, Mountain View, California

2. The Cylindrically Constricted DC Thermal Arc with Axial Air Flow - A Comparison of the Simplified Theoretical Model With Experimental Results
   V. R. Watson
   NASA Ames Research Center, Mountain View, California

3. Description of a Seeded Gas Plasma for a Low Density Wind Tunnel
   W. Christiansen
   Jet Propulsion Laboratory, Pasadena, California

4. Heat Transfer from Ionized Argon
   P. F. Massier
   Jet Propulsion Laboratory, Pasadena, California

5. Discharge, Acceleration, Diffusion and Recombination in Plasma Flows Subjected to Steady Applied Fields
   G. R. Russel
   Jet Propulsion Laboratory, Pasadena, California

(BREAK)

6. Transport-Equations for a Partially Ionized Gas in an Electric Field
   P. M. Sockol
   NASA Lewis Research Center, Cleveland, Ohio

7. Theory of Non-Equilibrium Flows in Crossed Electric and Magnetic Fields
   G. R. Russel
   Jet Propulsion Laboratory, Pasadena California

8. Non-Equilibrium Ionization in the Presence of Electric and Magnetic Fields
H. Hassan
North Carolina State University, Raleigh, North Carolina

9. Non-Equilibrium Ionization in Steady Discharges Crossed with Magnetic Fields for High Pressure MHD Studies
W. Grossmann, R. V. Hess, G. Oertel, F. W. Bowen, N.W.Jalufka
NASA Langley Research Center, Hampton, Virginia

10. Progress Report on the Design and Performance Study for a Crossed-Field Plasma Accelerator for a Reentry Facility
P. Lenn, G. Bedjai, D. Ward, B. Wilkinson
Northrop Company, Hawthorne, California
R. C. Brumfield, V. H. Blackman
MHD Research Corporation, Newport Beach, California

11. Research on Linear Crossed-Field Steady Flow Accelerators
A. F. Carter, A. P. Sabol, D. R. McFarland, W. Waever, G. P. Wood
NASA Langley Research Center, Hampton, Virginia

12. Reduction of Electrode Erosion in Continuous Plasma Accelerators Through Use of Externally R-F Heated Ring Cathodes
R. H. Weinstein, R. V. Hess, O. Jarrett, D. R. Brooks
NASA Langley Research Center, Hampton, Virginia

13. Magnetic Expansion Plasma Thrustor - Part I
G. R. Seikel
NASA Lewis Research Center, Cleveland, Ohio

14. Magnetic Expansion Plasma Thrustor - Part II
S. Domitz
NASA Lewis Research Center, Cleveland, Ohio

<u>Tuesday Afternoon, 3 Dec. 1963</u> 2:00 p.m.

SESSION IV: <u>AC Plasma Acceleration and Hall-Current Accelerators</u>
Chairman: R.V.Hess, NASA Langley Research Center

1. Travelling-Wave Accelerator
M. Lessen
University of Rochester, New York

2. The Travelling Magnetic Wave Plasma Engine
R. E. Jones, R. W. Palmer
NASA Lewis Research Center, Cleveland, Ohio

3. Travelling Wave Accelerator
W. H. Braun
NASA Lewis Research Center, Cleveland, Ohio

4. Inductive and Capacitive Heating of a Hydrogen Plasma by an RF Coil
   C. C. Swett
   NASA Lewis Research Center, Cleveland, Ohio

5. Continuous Microwave Magnetic Accelerator
   D. B. Miller
   General Electric Company, King of Prussia, Pennsylvania

(BREAK)

6. Hall Current Ion Accelerator
   D. L. Chubb, G. R. Seikel
   NASA Lewis Research Center, Cleveland, Ohio

7. The Hall Current Accelerator
   G. L. Cann
   Electro-Optical Systems Inc., Pasadena, California

8. Hall Currents and Oscillations for Steady Low Pressure Discharges with Crossed Magnetic Fields, Theory
   R. V. Hess, P. Brockman
   NASA Langley Research Center, Hampton, Virginia
   H. A. Hassan
   North Carolina State University, Raleigh, North Carolina

9. Hall Currents and Oscillations for Steady Low Pressure Discharges with Crossed Magnetic Fields, Experiments
   B. Sidney, J. Burlock, P. Brockman, R. V. Hess
   NASA Langley Research Center, Hampton, Virginia

Wednesday Morning, 4 Dec. 1963 — 9:00 a.m.

SESSION V: Plasma-Wave Interaction
Chairman: E. H. Holt, Rensselear Polytechnic Institute, Troy, New York

1. Electromagnetic Wave Propagation in Magneto Plasmas
   D. A. Hutchital
   Rensselear Polytechnic Institute, Troy, New York

2. Microwave Cavity Measurement of The Faraday Effect in a Glow Discharge Plasma
   F. R. Crownfield, Jr.
   College of William and Mary, Williamsburg, Virginia

3. Guided Waves in an Anisotropic Plasma
   A. M. Ferendeci
   Case Institute of Technology, Cleveland, Ohio

4. Propagation and Dispersion of Hydromagnetic and Ion Cyclotron Waves in Plasmas Immersed in Magnetic Fields
A. A. Dougal
The University of Texas, Austin, Texas

5. The Absorption of Vertically Polarized Plane Electromagnetic Waves in Thin Slabs of Plasma
P. D. Rowley
NASA Ames Research Center, Mountain View, California

6. Characteristics of a Magnetically Confined Steady State Plasma Beam
D. A. Meskan, R. E. Collin
Case Institute of Technology, Cleveland, Ohio

7. Reflection of a EM-Wave from a Shockfront
W. H. Eggimann
Case Institute of Technology, Cleveland, Ohio

8. Electromagnetic Wave Coupling to Magnetized Plasmas
M. Katzin
The Electromagnetic Research Corp., College Park, Maryland

9. Interaction of Plasma Oscillations with Conduction in a Penning Gauge
F. R. Crownfield
College of William and Mary, Williamsburg, Virginia

(BREAK)

SESSION VI: Magnetohydrodynamics
Chairman: V. J. Rossow, NASA Ames Research Center

1. Stability of Magnetohydrodynamic Configurations
Eli Reshotko
NASA Lewis Research Center, Cleveland, Ohio

2. Structure of Shock Waves in Collision-Free, Tepid Plasmas
W. P. Jones, V. J. Rossow
NASA Ames Research Center, Mountain View, California

3. Hypersonic Magnetohydrodynamics
R. H. Levy, E. V. Locke, H. E. Petschek, P. H. Rose
Avco Everett Research Laboratory, Everett, Massachusetts

4. Magnetoaerodynamic Drag and Shock Stand-Off Distance
T. P. Anderson, Ching Shi Liu, R. C. Warder, Jr., A. B. Cambel
Northwestern University, Evanston, Illinois

5. Preliminary Tests in the JPL Liquid Sodium Tunnel
T. Maxworthy
Jet Propulsion Laboratory, Pasadena, California

Wednesday Afternoon, 4 Dec. 1963 — 1:30 p.m.

SESSION VII: Plasma Energy Conversion
Chairman: G. Seikel, NASA Lewis Research Center

1. Theoretical Current-Voltage Curve in Low-Pressure Cesium Diode for Ion-Rich Emission
C. M. Goldstein
NASA Lewis Research Center, Cleveland, Ohio

2. The Effects of Electron Heating and Ion Slip on the Performance of an MHD Generator
F. A. Lyman
NASA Lewis Research Center, Cleveland, Ohio

3. MHD Power Generation With Non-Equilibrium Ionization
L. D. Nichols
NASA Lewis Research Center, Cleveland, Ohio

4. Rotating MHD Induction Generators
R. E. Schwirian, E. J. Morgan
Case Institute of Technology, Cleveland, Ohio

5. A MHD Electric Power Generator Using Seeded Combustion Products of Cyonogen and Oxygen
I. Fruchtmann
NASA Langley Research Center, Hampton, Virginia

6. MHD A-C Power Generation
H. H. Woodson
Massachusetts Institute of Technology, Cambridge, Mass.

(BREAK)

SESSION VIII: Plasma Diagnostics
Chairman: O. K. Mawardi, Case Institute of Technology

1. Experimental Probing of Plasmas with Optical Lasers
A. A. Dougal
The University of Texas, Austin, Texas

2. Rate of Energy Loss of Energetic Electrons in a Plasma, Part I, Theoretical
M. R. Smith, W. B. Johnson
Case Institute of Technology, Cleveland, Ohio

I, 1

PLASMA KINETIC THEORY

D.A. Tidman
University of Maryland
College Park, Maryland

NsG 220-62

Our research is in the field of fundamencal plasma kinetic theory with applications to problems in space physics. Some of our current activity is the following:

Drs. Montgomery and Tidman have been studying methods for obtaining asymptotic series solutions to non-linear differential equations (methods developed by Bogoliubov, Krylov, and others). We have applied these methods to calculate some frequency shifts which occur in non-linear waves in cold plasmas. These may be detectable in laboratory plasmas.

The problem of the structure of a plasma shock wave in a hot plasma is being attempted using these techniques. It seems possible to calculate the asymptotic structure of the leading edge of a shock wave this way. A rigourous shock wave theory is a prerequisite for any theory of Type II solar radio outbursts. These bursts are thought to originate in shock waves in the solar corona - but no convincing theory for them yet exists.

Dr. Guernsey has succeeded in deriving a divergence - free kinetic equation for a plasma. The most fundamental kinetic equation derived to date is the so-called Balescu-Lenard equation. (the counterpart for a Coulomb gas of the Boltzmann equation for a molecular gas) However the Balescu-Lenard equation has been plagued by a divergence associated with the short range part of the coulomb potential, and which previously was removed by an unsatisfactory cut-off procedure.

The following problems are being carried out by students:

A study of initial value problems (using a computer) for the Guernsey-Balescu-Lenard equation in its exact non-linear form is being made. The simplifying assumption which makes this possible is to restrict consideration only to homogeneous plasmas in which the velocity distributions are isotropic.

Wave propagation in relativistic plasmas is being studied using the relativistic Vlasov equations.

I, 2

PRECEDING PAGE BLANK NOT FILMED

STUDIES OF PAIR-CORRELATIONS IN PLASMA THEORY

C. S. Wu, E. H. Klevans, J. S. Zmuidzinas
Jet Propulsion Laboratory
Pasadena, California

We have started a series of systematic studies on various fundamental problems in plasma physics. The approach is based on the so-called BBGKY hierarchy equations. The purpose of the research is to investigate the effects of the two-particle correlations in numerous plasma phenomena. Extensive study along this line seems to be very significant and important in the most recent development of advanced plasma kinetic theory. In the past few years, the self-consistent field approximation (or the Vlasov theory) based on the collisionless Boltzmann equation has been extensively exploited and been proved very useful to understand many high-frequency wave and stability problems in a plasma. The theory indeed gives fairly accurate results for the wave dispersion relation for a high temperature and low density plasma. This is reasonable since the wave frequency is usually much higher than the collision frequency, so that collision cannot produce any important effect. However, for the phenomena of damping or growth of the waves, the characteristic time scale may be of the same order as the collision time and thus the two-particle correlations may give rise to significant modifications to the results obtained from collisionless theory. This conjecture has been verified in the first of a series of theoretical studies taking place here.(1) We have extended the Landau Vlasov theory of plasma oscillations, which indicates that in the long wavelength limit the damping would vanish, and found a damping independent of wave number K due to electron-ion correlation. Since this correlation damping is much greater than the Landau damping, one may easily imagine the correlation would tend to stabilize or to delay those microinstabilities predicted by the collisionless theory. This

(1) Wu, C. S. and Klevans, E. H., "Theory of Plasma Oscillations with Pair Correlations" to be published in the Proceedings of 6th International Conference on Ionization Phenomena in Gases, Paris, France, July, 1963.

motivates us to re-examine the well known two stream instability with binary correlation taken into account.

At the present time, our group is investigating several problems simultaneously, all based on the kinetic theory with two-particle correlations. These problems can be listed as follows:

1. The effect of different electron and ion temperatures on conductivity,

2. Electron-ion temperature relaxation,

3. Kinetic equation for a plasma in a weak external electric field,

4. As an extension of (3), the electron runaway phenomenon,

5. Effect of pair-correlations on a two stream instability.

I, 3

REENTRY HEAT TRANSFER AND PLASMA STATISTICS

by

Willard E. Meador, Jr.
NASA Langley Research Center
Hampton, Virginia

Efforts to understand the mechanisms of energy, mass, momentum, and charge transfer from one region of a gas to another, for example heat flux through the boundary layer of a reentering space vehicle, necessarily involve two general areas of study: (1) collision dynamics (evaluation of Hirschfelder omega integrals and/or Chandrasekhar diffusion coefficients), and (2) statistical frameworks in which the collisions occur. Research at Langley has been concerned primarily with the quantum mechanical aspects of particle interaction potentials up to and including dissociation products, some results being obtained at the same time in such sideline topics as basic quantum and statistical theories, statistical simplifications, Liouville chain breaking, relativistic effects, inelastic collisions, and resonant exchange phenomena. These will be discussed in more or less general terms with the main emphasis on the following two current projects, they being the ones most pertinent to plasma physics.

Project I is an evaluation of the binary diffusion model in connection with stagnation point heat transfer. This model treats a partially ionized gas as consisting of only two components, molecules on the one hand and atoms, ions, and electrons on the other, for purposes of calculating reaction thermal conductivity. It is felt that previous applications of this technique all involved unrealistic assumptions concerning the behavior of ions and charge exchange effects on off-diagonal matrix elements; reasons for this speculation, partly supported by data already obtained, will be presented. New ways of determining electron-electron, electron-ion, and ion-ion cross sections will be listed, as well as a discussion on the physical interpretations of diffusion models and boundary layer properties (frozen versus equilibrium, atomic insulation or not).

Project II is an attempt to develop systematic checks on binary collision statistics such as the Boltzmann and Fokker-Planck equations. Long range coulomb forces are such as to

render extremely dubious the assumptions that multiple interactions are not important and that cluster effects apart from deDye shielding do not occur. Of particular interest is the possibility that these clouds become somewhat warped and difficult to form as the temperature increases. In this connection the conditions for the validity of Vlassov's equation have been made more explicit and a method outlined for introducing collision terms in a formal way, the next step being a derivation and check of Fokker-Planck correlation functions.

As time permits, discussion will be offered concerning our present feelings on resonant and nonresonant charge exchange, electron-neutral quantum collisions and statistics for partially ionized gases.

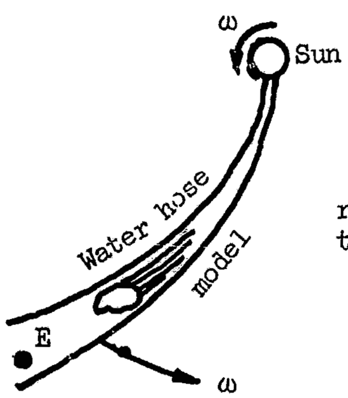
I, 4

MHD PROBLEMS RELATED TO THE INTERPLANETARY MAGNETIC FIELD

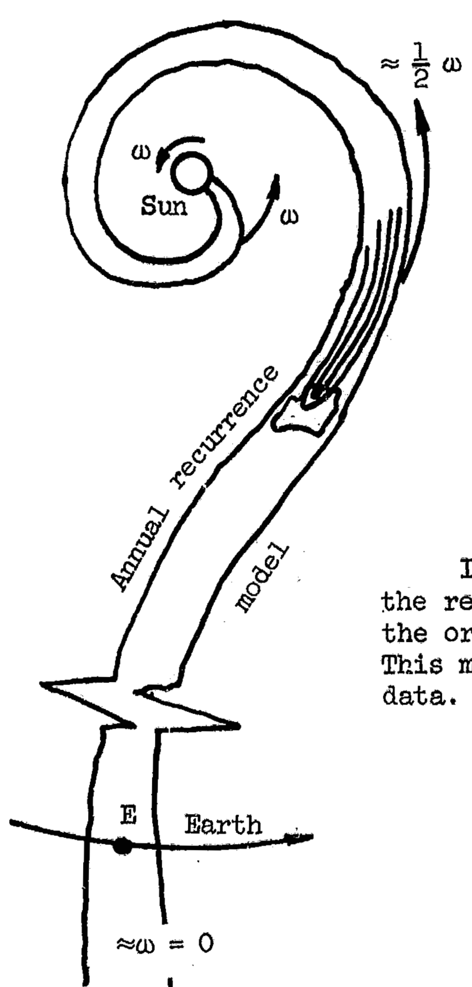
D. Adamson
NASA Langley Research Center
Hampton, Virginia

An investigation of the stability of the bounding surface of the magnetospheric cavity is being made. Whether or not this interface is stable has important bearing on a variety of geophysical phenomena. In view of the sparsity of particles in the neighborhood of the interface (some tens per cm^3), the assumption of continuum flow invoked in analyses made to date is open to question. Further thought is being given to this problem. It appears that by virtue of the existence of an interplanetary magnetic field a constraint is placed on the particle motions and "modified" continuum equations are applicable. The outcome of these basic considerations have not only relevance to the problem of interface stability but will reflect on all aspects of behavior of the interplanetary medium and the kinds of instability to which it may be subject.

In an investigation made recently and reported in NASA TN D-1010 a correlation was established between the occurrence of solar proton events and intense geomagnetic storms (those having an A_p index exceeding 80). A subsequent superficial statistical analysis of such intense storm data revealed a periodicity of approximately 12 months which was thought to indicate that the magnetic fields at the earth's orbital distance are stationary instead of corotating with the sun. Actually, a more detailed analysis has disclosed the periodicity is more nearly 13 months, indicating a slow rotation of the magnetic fields in the direction of the earth's motion. Such a concept is at variance with the water hose model.



In water hose model, recurrence would be every 27 days, the rotation period of sun.



In annual recurrence model, the recurrence period would be the orbital period of the earth. This model is supported by the data.

9

I, 5

THEORY OF SOLAR WIND-GEOMAGNETIC FIELD INTERACTION

C. C. Chang
Catholic University
Washington, D. C.

I, 6

EXPERIMENTAL STUDY OF DISCHARGE AT NEUTRAL POINT

A. Bratenahl
Jet Propulsion Laboratory
Pasadena, California

Currently in preparation is an experiment to facilitate the study of a discharge at a neutral point in a magnetic field. Isolated points, lines, or planes, where the field vanishes, we shall refer to as "neutral points." If the field lines encircle the point, we shall call it an O-point. If the field lines are hyperbolic in the neighborhood of the point we shall call it an X-point. Through the agency of a neutral point the total flux of a system may be changed. The X-point is of special interest in a plasma since, besides the total flux, the general topology of the field may be changed through the severing and reconnection of lines of force. These matters are systematically discussed by Dungey.(1)

The process at an X-point can evolve very rapidly even in systems where the conductivity is extremely high and the hydromagnetic approximation is valid. In this case, the usual assumption of infinite conductivity everywhere must be abandoned at least in the neighborhood of the point and due account paid to the fact that all natural plasma systems have a finite resistivity.

The X-type neutral point is of general interest in hydromagnetic plasmas on the astrophysical scale. For example, it is an essential ingredient in Babcock's theory of the solar magnetic dynamo.(2) A rather dramatic example in solar physics is almost certainly to be seen in the flare, which is currently understood in terms of an explosive release of stored magnetic energy at a neutral point.(3...8) On the other hand, Parker(9) has prepared a rather exhaustive summary and analysis of various theories of the solar flare, and concludes that no presently proposed theory is adequate to explain it. He then makes several interesting alternative suggestions including the possibility that some unknown instability might be present.

Simultaneously, but quite independently of Parker's study, Furth, Kileen and Rosenbluth(10) identified not one but three instabilities at X-type neutral points and calculated their rates of growth. Although their analysis was applied to a study of laboratory plasmas of controlled thermonuclear interest, Jaggi(11) has already applied their

theory to the solar flare with interesting results. It is clear that current theoretical treatments differ rather widely in essential points and one is left with the impression that some experimental studies might be helpful and timely.

Our current experiments produce an X-type neutral point along the line of contact formed at the instant of collision of two outwardly expanding cylindrical shock waves. These shock waves are produced by two inverse pinch devices mounted side by side in a common vacuum system. The advantage of this arrangement lies in the fact that the initial and final states of the system are well behaved and can be calculated with reasonable confidence. The transition, which involves a change in topology of field lines, will be studied by well known techniques, for example, magnetic probes and the Kerr cell camera.

We are under no illusion that we are making a working scale model of the solar flare. What we hope to do, is gain some insight through experiment to a problem that turns out to be somewhat more complicated than had heretofor been supposed. For example, it may be expected that the behavior at an X-type point would be strongly dependent on the relation of the initial state of the system to those final states that are topologically accessible to it through the agency of the neutral point itself. Hence contrary to Dungey's simplified analysis, the intrinsic property of the point is not likely to be the primary factor determining the transition.

REFERENCES

(1) Dungey, J. W., Cosmic Electrodynamics, Cambridge University Press, 1958.

(2) Babcock, H. W., Ap. J. 133, 572 (1961).

(3) Giovanelli, R. G., M. N. Roy. A. Soc. 107, 338 (1947).

(4) Severnyi, A. B., Sov. Astr. A. J. 2, 310-325 (1958); Sov. Astr. A. J. 5, 299 (1961); Sov. Astr. A. J. 4, 583 (1961); and many others.

(5) Gold, T., Hoyle, F., M. N. Roy. A. Soc. No. 2, 120, 89 (1960).

(6) Deubner, F-L., Zeit. fur A. 55, 123, 1962.

(7) Sweet, P. A., IAU Symposium on Electromagnetic Phenomena in Cosmical Physics No. 6, 123 (1958).

(8) Howard, R. and Severnyi, A. B., Ap. J. 137, 1242 (1963).

(9) Parker, E. N., Ap. J. Sup. No. 77 Vol. VIII, abstract appears in Ap. J. 138, 310 (1963).

(10) Furth, H. P., Killeen, J., Rosenbluth, M. N., Phys. Flu. 6, 459 (1963).

(11) Jaggi, R. N., J. Geophys. Res. 68, 4429, (1963).

I, 7

THREE BODY COLLISIONAL RECOMBINATION OF CESIUM IONS AND ELECTRONS IN AN OPTICALLY THIN PLASMA

J. V. Dugan, Jr.
NASA Lewis Research Center
Cleveland, Ohio

The rate of three body recombination between cesium ions and electrons in a non-equilibrium plasma is calculated employing the method of Byron et al.[1,2,3] The main postulate of the Byron model is that de-excitation of bound electrons from excited states is the rate limiting step in the kinetics of recombination. Once captured, the rate at which electrons can reach the ground state (recombination) is governed solely by the rate at which superelastic collisions cause de-excitation, R_{DEX}. These scattering events occur when free electrons receive the de-excitation energy of the atomic collision as kinetic energy. This de-excitation rate is computed for all states and is found to have a minimum at a particular energy level for a given electron temperature. This minimum rate is effectively the recombination rate. Radiative emission is neglected as a de-excitation process in the range of electron densities considered and all atomic levels are assumed to be in equilibrium with the free electrons.

The cross section for atomic excitation as derived by Gryzynski[4] is utilized with the statistical mechanical principle of detailed balancing to compute R_{DEX} through the various energy levels. Seventy-two known electronic levels[5] of the cesium atom are treated discretely for each transition. Byron et al obtained R_{DEX} for potassium by assuming that a continuum of levels existed above and below any level E*. Also, the exact form of the inelastic cross section has been used rather than the approximation of reference 3.

The model is applied to a cesium seeded argon plasma (of interest for MHD generator work) where Cs^+ is the only ion in the range of electron number densities N_e, 10^{13} -10^{18} cm^{-3}, and electron temperature Θ_e, 500-10,000° K. Trapping of emitted radiation was ignored.

Supplementary calculations were made employing the D'Angelo[6] recombination model where competing steps are considered with electrons "traced" through the atomic levels. When Bohr-Thomson inelastic cross sections are used, the method yields a divergent recombination rate. A similar calculation using the Gryzynski cross sections is now in progress.

Results are within an order of magnitude of reference 3 but the plot of R_{DEX} vs Θ_e display more fine structure and the minima for cesium are shifted from the potassium values. It can be safely concluded that the attainment of conductivety levels necessary for MHD power generation will be difficult especially at temperatures below 3000° K.

References:

1. Petschek, H. and Byron, S.: Annals of Physics 1 270, 1957.
2. Byron, S., Stabler, R.C., and Bortz, P.I.: Phys. Rev. Letters 8, 376, 1962.
3. Byron, S., Bortz, P.I., and Russell, G.R.: Proc. Fourth Symp. on Eng'g. Aspects of MHD. April 1962.
4. Gryzynski, M.: Phys. Rev. 115, 374, 1959.
5. NBS Circular 467, Vol. 3, U.S. G.P.O., 1952.
6. D'Angelo, N.: Phys. Rev. 121, 505, 1961.

I, ..8

THE AFTERGLOW TECHNIQUE IN PLASMA RESEARCH

E. H. Holt, R. E. Haskell[1], J. S. Mendell[2]
Rensselaer Polytechnic Institute
Troy, New York

The paper reviews a number of projects recently completed at Rensselaer. An analysis of the plasma afterglow in nitrogen has been made using multiple diagnostic techniques[1]. This work is reported by K. C. Stotz in a separate paper. In connection with it a gated microwave radiometer has been developed[2] which detects a 10°K. difference between the temperature of the electron gas of the plasma and the temperature (room) of the ion and neutral molecule gas. With larger temperature differences a time resolution of the temperature variation of the electron gas to within 1 microsecond can be made.

A new theoretical approach to the problem of electromagnetic wave propagation in magnetoplasmas has been formulated and experimentally verified[3,4]. The electromagnet used in this work is of a particularly simple and flexible design[5]. A magnetic field of 10,000 gauss is generated in a volume 16 inches long and 6 inches in diameter by a flat helix of 100 turns which is energized by a bank of wet cells. The magnet operates for one minute at a time and no cooling arrangements are necessary. The magnetoplasma is represented by a transformation matrix which operates on the input wave to produce the output wave. The terms of this matrix are functions of the orthogonal components of certain input and output wave polarizations. If the response of the medium to these wave polarizations can be measured, then the transformation matrix can be calculated and the behavior of the medium for all other waves can be predicted. The experimental circuit used to verify this theory is shown in Figure 1. A K-band klystron supplies a signal which is given a pre-determined polarization by means of suitable microwave components. This wave is laundered along the axis of the magnetic field. It traverses a plasma created by a pulse of r.f. energy at 4.7 mc. The output wave impinges on a second conical horn and is guided into a trimode turnstile junction which serves as a polarimeter to divide the wave into orthogonal components. After two stages of heterodyning the two signals are applied to the plates of an X-Y oscilloscope and the polarization ellipse of the wave is displayed directly. The transformation matrix has been measured for this experimental arrangement. It has been used to predict the wave polarization which propagates unchanged through the plasma and the wave polarization which propagates with maximum intensity.

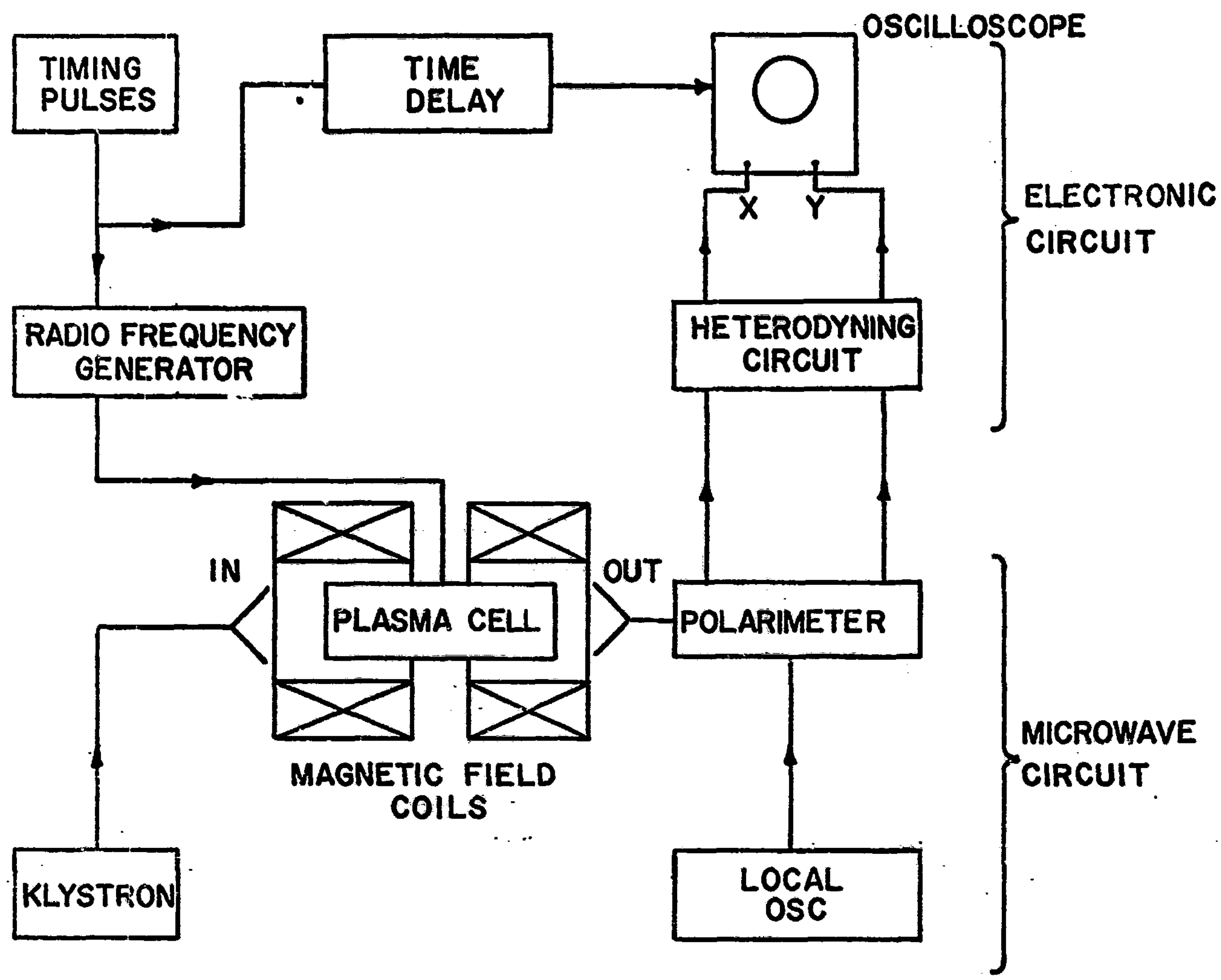
1 Now at Air Force Cambridge Research Laboratory, Bedford, Mass.
2 Now at Pratt and Whitney Aircraft, E. Hartford, Conn.

A study of the interaction between a quiescent plasma and a bunched, relativistic electron beam has been made both theoretically and experimentally[6]. The purpose of the work was to detect radiation outside the plasma vessel due to the propagation of Cerenkov-type waves in the plasma electron gas. Such waves were expected to be generated by the electron bunches of the beam. The experimental arrangement is shown in Figure 2. The high voltage generator is pulsed to produce plasma in the cell at discrete intervals. The plasma density is monitored by means of a microwave bridge. At pre-determined times in the afterglow the linear accelerator is triggered and a burst of electron bunches is fired through the plasma. Provision was made to detect the radiation with a microwave receiver. No radiation above threshold was detectable showing that the radiation produced must have a power level of less than 0.4×10^{-10} watts per cm. path traversed by the beam.

REFERENCES

1. K. C. Stotz, "Investigation of Plasma After Glows with Application in Nitrogen", Rensselaer Polytechnic Institute, Plasma Research Laboratory, Tech. Rep. No. 9, June 1963.
2. W. C. Taft, K. C. Stotz, E. H. Holt, "A Gated Radiometer for Plasma Afterglow Study", Trans. IEEE Instrumentation and Measurement, (to be published).
3. R. E. Haskell, E. H. Holt, "Study of Electromagnetic Wave Polarization in Magneto-Plasmas by a Matrix Method of Crystal Optics", Proc. IRE, 49, 1584 (October 1961).
4. R. E. Haskell, "Polarization Transforming Properties of Anisotropic Plasmas", Rensselaer Polytechnic Institute, Plasma Research Laboratory, Tech.Rep.No. 8, August 1963.
5. J. E. Rudzki, E. H. Holt, "Ten Kilogauss, Air Cooled Magnet for Plasma Research", Rev. Sci. Instr., 34, 1155, October 1963.
6. J. S. Mendell, "Investigation of Plasma Oscillations Stimulated by a Pre-Bunched Electron Beam from the Rensselaer Accelerator," Rensselaer Polytechnic Institute, Ph. D. Thesis, September 1963.

EXPERIMENTAL CONFIGURATION



THEORETICAL FORMULATION

$$[\text{OUTGOING WAVE}] = [\text{PLASMA}] \times [\text{INCOMING WAVE}]$$

$$\begin{bmatrix} E_1^{OUT} \\ E_2^{OUT} \end{bmatrix} = \begin{bmatrix} \text{M} \\ \text{MATRIX} \end{bmatrix} \times \begin{bmatrix} E_1^{IN} \\ E_2^{IN} \end{bmatrix}$$

FIGURE 1

ELECTROMAGNETIC WAVE PROPAGATION THROUGH A PLASMA IN A MAGNETIC FIELD

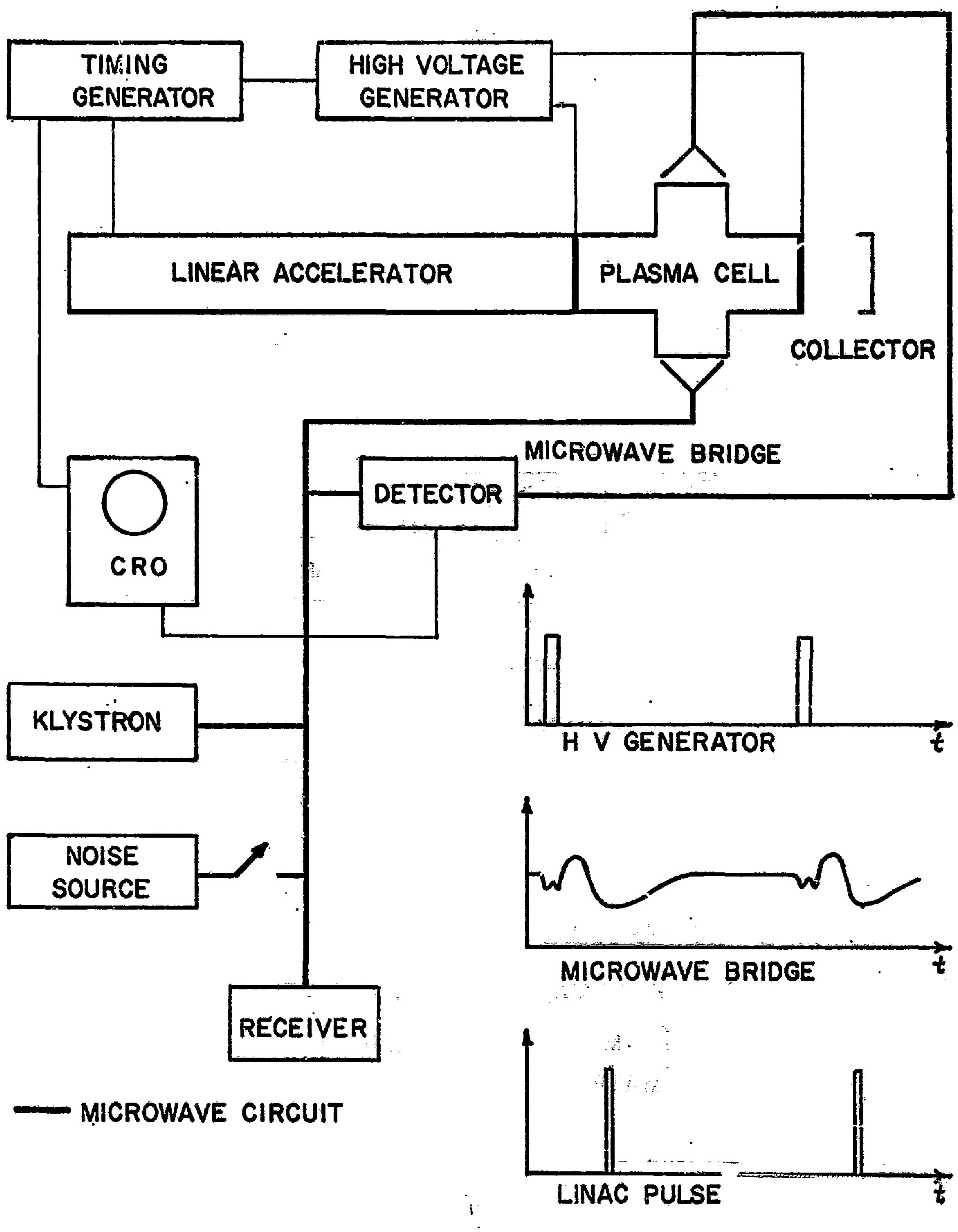


FIGURE 2

INVESTIGATION OF PLASMA OSCILLATIONS STIMULATED BY A
PRE-BUNCHED ELECTRON BEAM FROM THE RENSSELAER ACCELERATOR

I, 9

ELECTRON COLLISION PHENOMENA IN NITROGEN

K. C. Stotz
RENSSELAER POLYTECHNIC INSTITUTE
Troy, New York

There is a continuing need for cross-section measurements of electron collision processes in gases. Bourdeau[1], for example, has pointed to the need of data on the recombination coefficient in atmospheric gases in order to understand ionospheric phenomena. This paper reports the results of a study of electron collision processes in nitrogen obtained by the afterglow technique. Multiple diagnostic techniques were used to arrive at a clear understanding of the experimental conditions.

A block diagram of the apparatus is shown in Figure 1. The basic microwave interferometer shown by the solid lines is used to obtain measurements of the electron density and collision frequency. In the past, coefficients obtained using the interferometer circuit have differed from values obtained by the cavity technique. It was suspected that the difference could be accounted for by the fact that the electrons had not relaxed to room temperature in early interferometer experiments. Therefore a gated microwave radiometer[2] was developed and used to monitor the electron temperature in the afterglow. It is shown schematically as the dotted lines in the figure. Results employing this device have verified that earlier measurements were made in non-thermal plasmas.

The monochromator in the figure was used in an attempt to identify the ions through visible spectra. Only N_2 spectra were obtained, but this does not eliminate the presence of the N_4^+ ion (since dissociative recombination of N_4^+ would be indicated by the presence of an N_2 spectra).

The ambipolar diffusion coefficient times pressure obtained for nitrogen is, $D_a p = 123 \pm 24$ cm^2 Torr sec^{-1} in the pressure range 0.2 to 4.5 Torr at room temperature. This corresponds to a mobility at 0°C, 760 Torr of 2.85 cm^2 sec^{-1} volt^{-1}. The recombination coefficient increases with pressure from 4×10^{-8} cm^3 sec^{-1} at 0.25 Torr to 6.8×10^{-7} cm^2 sec^{-1} at 7.1 Torr. The recombination mechanism is attributed to the dissociative recombination of the N_4^+ ion, although the three-body recombination of the N_2^+ ion may play a significant role. The

temperature measurements have indicated a source of hot electrons in the early afterglow which has been attributed to the presence of metastable molecules.

Further temperature measurements are in progress and a time of flight mass spectrometer is under construction to provide data on the density of the several ion species as a function of time in the afterglow.

In the future it is proposed to apply these multiple diagnostic techniques to the measurement of transport coefficients in the presence of a magnetic field. This program is discussed further in the paper by D. A. Huchital.

1. Bourdeau, Robert E., "Space Flight Studies of the Ionosphere", Proc. of the NASA-University Conference on the Science and Technology of Space Exploration, Vol. 1, NASA SP-11, p. 118, December 1962.

2. Taft, W. C., Stotz, K. C., Holt, E. H., "A Gated Radiometer for Plasma Afterglow Study", Trans. IEEE Instrumentation and Measurement, (to be published).

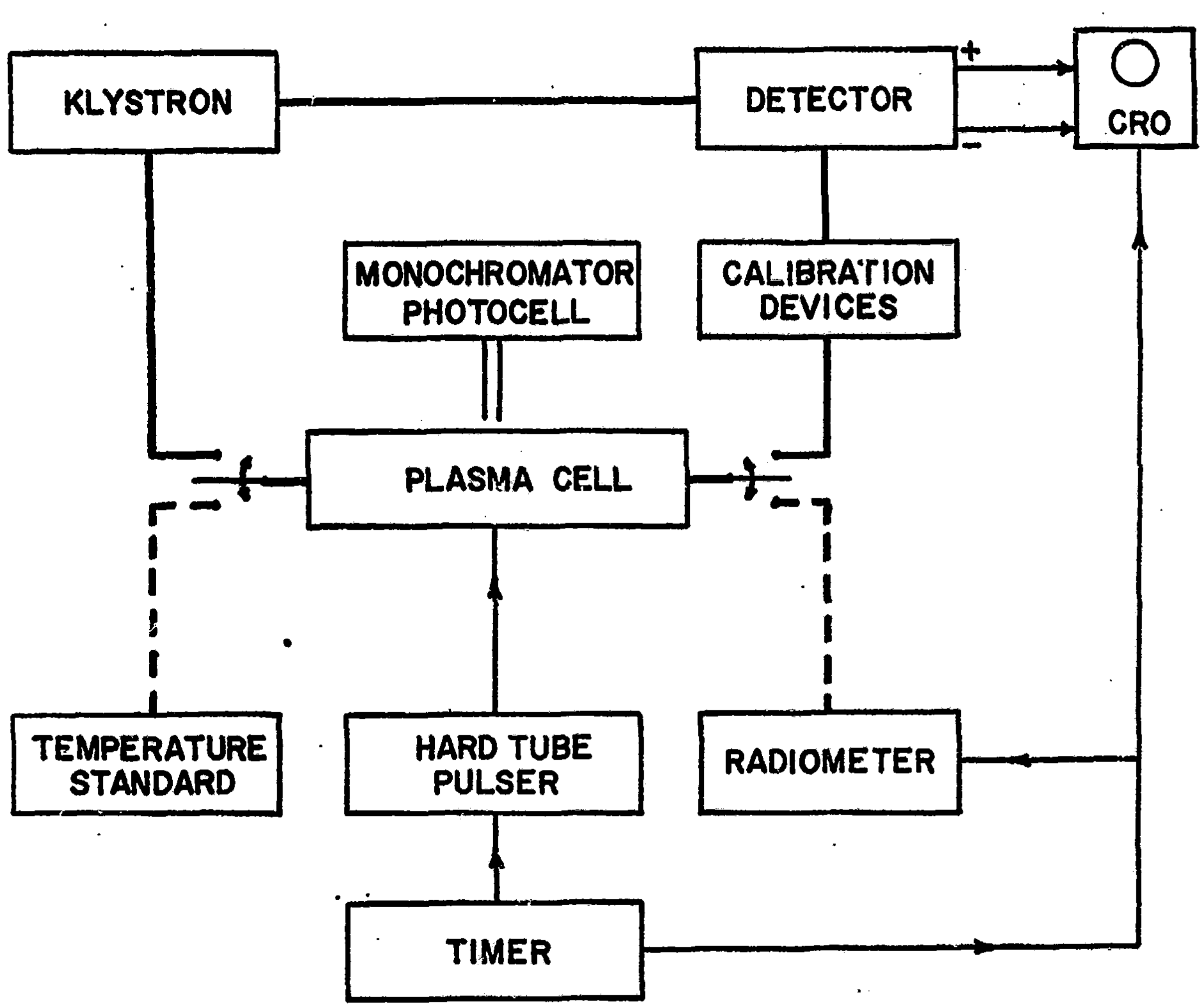


FIGURE 1

MICROWAVE DIAGNOSTICS FOR PLASMA AFTERGLOW STUDY

I, 10

VOLUME ION PRODUCTION COST AND SPECTROSCOPIC DIAGNOSTICS IN A HELIUM PLASMA

R. J. Sovie
NASA Lewis Research Center
Cleveland, Ohio

A theoretical calculation of the energy required for volume ion production has been made for the core of a partially ionized helium plasma that is optically thin and in which a Maxwellian distribution of electron velocities prevails. Inelastic electron-atom collisions that result in excitation of atomic energy levels are the only loss mechanisms considered. The energy requirement is computed by considering the rates for the competing processes of excitation and ionization. The results show that the energy required for volume ion production decreases sharply from 78 to 43.5 ev/ion as the electron kinetic temperature increases from 6 to 60 ev and then decreases slowly to 38.5 ev/ion at an electron kinetic temperature of 200 ev. The ion production rate and the power consumed in ion production for a steady state plasma have also been evaluated as a function of electron kinetic temperature. These quantities are found to increase at a decreasing rate as the electron energy is increased.

Investigation of a previously published spectroscopic diagnostic technique for determination of electron temperature and percent ionization in a helium plasma has shown that the results obtained by using this method will be pressure dependent due to the effects of secondary processes on the intensity ratios studied. This technique has been revised using helium excitation functions that are insensitive to pressure in the range 0 - 130 microns. The results of this revised technique are presented in the accompanying figure. In this figure the electron kinetic temperature is obtained directly from the observed intensity ratio of the helium neutral spectral lines at 5047 A and 4713 A. The quantity $F(kT_e)$ which is the ratio of the averaged excitationcross-sections of the 4686 A H_eII spectral line and the 5047 A H_eI line is then determined from the known value of the electron kinetic temperature. The percentage ionized, P, is then calculated by using $F(kT_e)$ and the observed intensity ratio of the 4686 A H_eII line and the 5047 A H_eI line.

E-2142

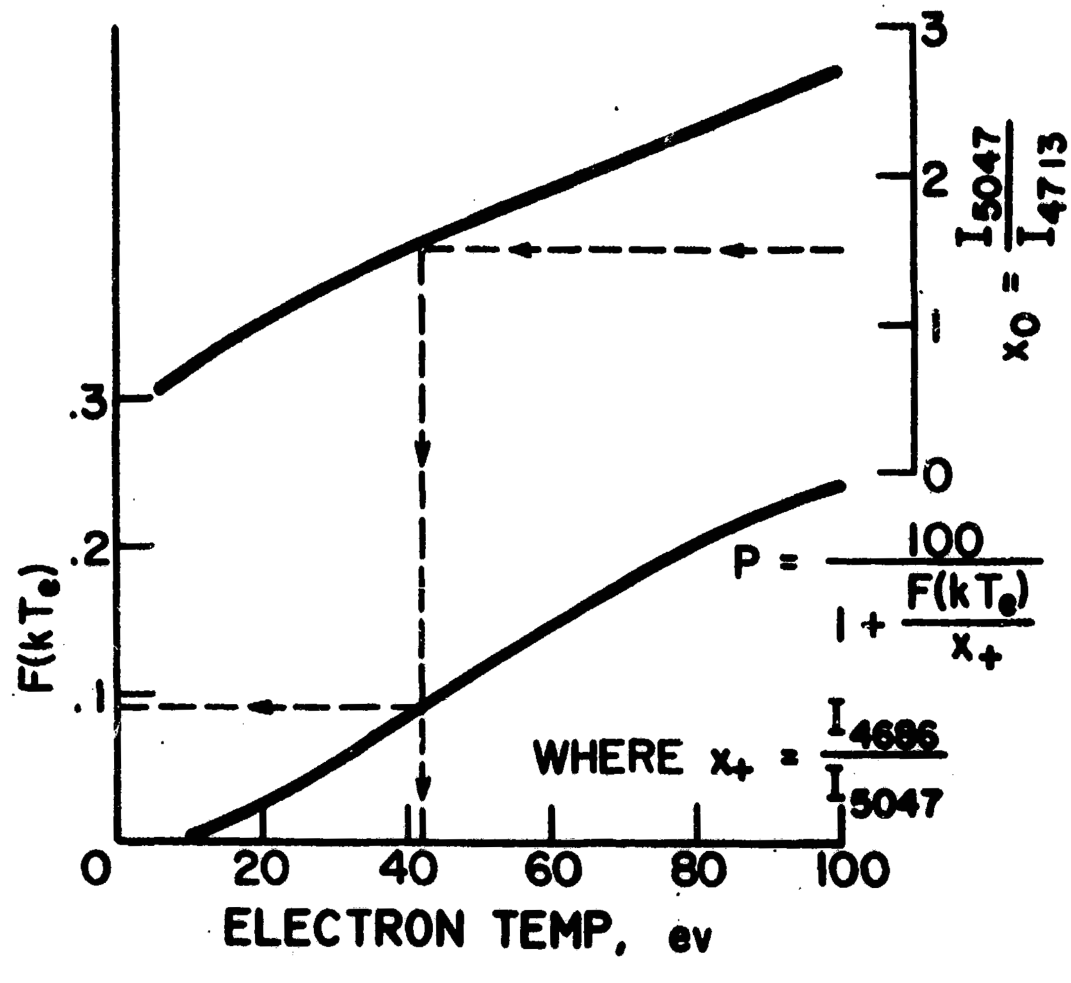


Figure No. 1

Determination of Electron Temperature and Percent Ionized from Observed Intensity Ratios

PRECEDING PAGE BLANK NOT FILMED

I, 11

ELECTRON BEAM MODE DISCHARGE STUDIES

J. Litton, Jr.
Electronic Systems & Products Division
Martin Company
Baltimore 3, Maryland

NASw-714

Under NASA contract NASw-714, The Martin Company is conducting research to determine the basic mechanisms of the Electron Beam Mode Discharge (Fig. 1). The work consists of a set of diagnostic experiments and their analysis in terms of events which cause a perforated or open wall hollow cathode discharge to generate a high impedance, energetic electron beam.

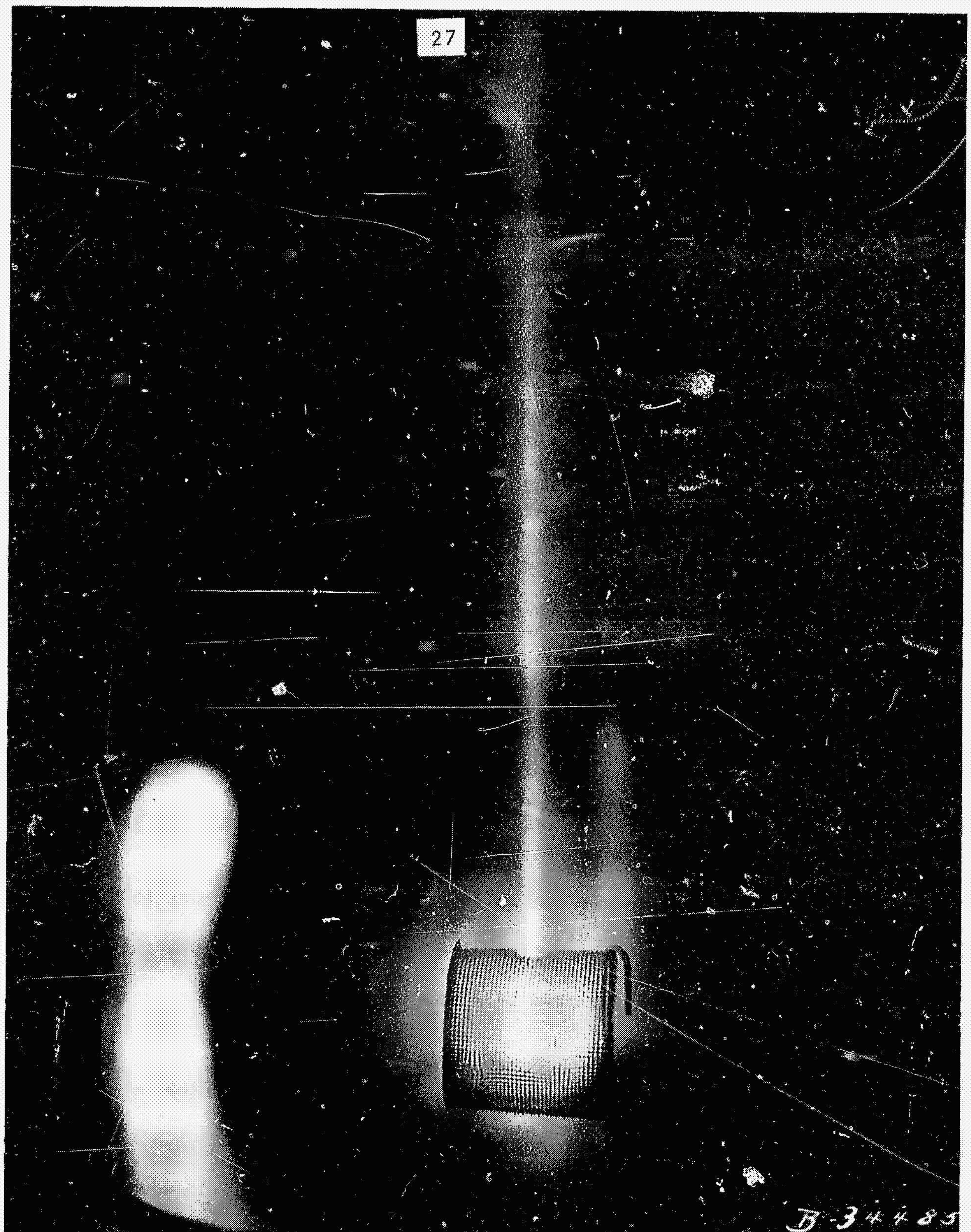
The various types of diagnostic experiments being conducted are: Langmuir probe, electron beam probe, microwave diagnostic and spectroscopic methods. These several approaches have resulted in data which does in fact indicate that the Electron Beam Mode Discharge is an entirely different form of discharge from its bi-stable mode in the same cathode. These results were first confirmed experimentally by observation of the Helium lines in the discharge.

The microwave studies have demonstrated the effect of the transparency of the mesh upon volume ionization interior to the negative glow. The Langmuir probe data indicates that electron densities in this region are higher, and electron temperatures lower, than intuitively expected for a high impedance discharge.

It is clear from both the Langmuir probe data and the spectroscopic data that the Electron Beam Mode Discharge is a fundamentally different effect from the normal hollow cathode discharge even when the latter is one of the modes of the same cathode which produces the Electron Beam Mode Discharge. Observation of spectral line intensity radiation in both the hollow cathode discharge and electron Beam Mode Discharge indicates the relative effect of electrons and positive ions in these two modes respectively are dominant. The orange line (5875Å) for the Electron Beam Mode Discharge is significantly larger than that of the hollow cathode discharge and the green line (5015Å) for the hollow cathode discharge is greater than that of the Electron Beam Mode Discharge. Classically, these

two lines have been used to indicate the occurrence of different types of ionization taking place. The green line is stronger when electrons produce the ionization and the orange line is stronger when positive ions are the ionizing agent.

The latest data and interpretation will be presented at the symposium, and a discussion of the experimental benefits of each of the methods being utilized will be given.


27
B-34485

I, 12

Electric Drag of Charged Spheres

W. C. Pitts and E. D. Knechtel
NASA Ames Research Center
Mountain View, California

Measurements have been made of the electric drag of conducting spheres having a charged surface, in order to obtain a better understanding of the electric-drag problem and to help resolve the differences between various theories. A broad mercury-plasma beam has been employed to permit simulation of the flow about a satellite in an ionized medium.

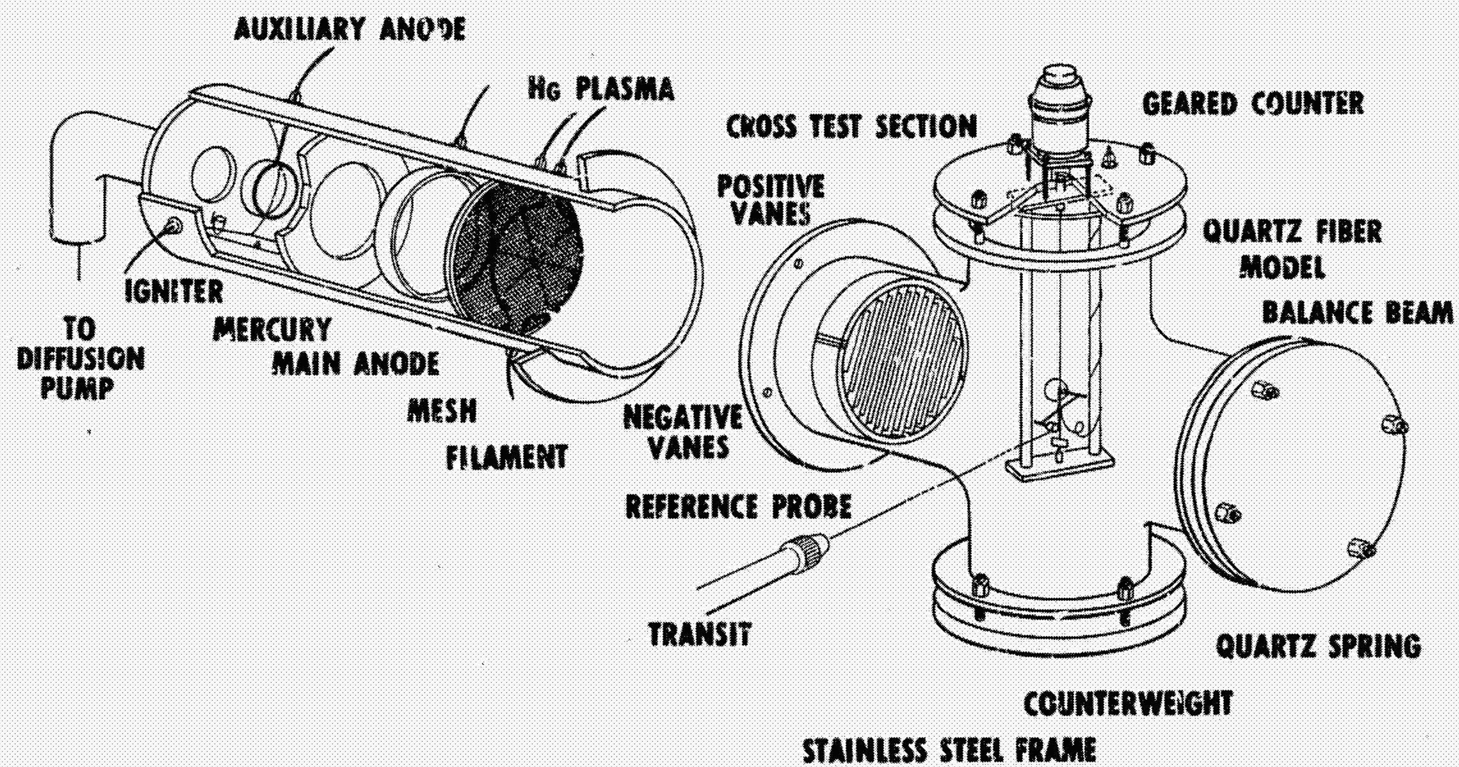
The experimental apparatus provides a directed mercury plasma beam variable in energy over the range from 60 to 300 electron volts, with a number density of approximately 10^8 ions per cc. and a useable core diameter of over five centimeters. Drag is measured with a quartz torsion microbalance operated remotely through the vacuum wall, with provision for electrical contact to control the model's surface potential. The satellite models are hollow glass spheres up to one inch in diameter, having a gold surface applied by vacuum evaporation. Diagnosis and control of the plasma beam was accomplished with Langmuir probes and a Faraday cage.

The ion drag results showed a definite effect of negative potential applied to the model surface and gave quite good agreement with the electric drag theories of Jastrow and Pearse and of Hohl and Wood, while ruling out various other theories for which the predicted drag was either much higher or much lower. To relate experimental results to

satellite conditions, it was found necessary to use three scaling parameters involving the surface potential, ion energy, ion number density, body size, and electron temperature. An empirical relation between the theoretical electric drag and the scaling parameters has been devised which covers the ranges of practical interest.

The conclusions from the ion drag measurements and correlations are that electric drag can be significant for certain practical conditions -- for instance, a 2-foot diameter spherical satellite at 600 miles altitude with a surface potential of -4 volts would have a drag of about one and one-half times that of the uncharged satellite. These results also indicate that for practical sizes of satellites, any electric-drag theory should account primarily for ion-surface collisions, as in the Jastrow-Pearse theory.

BROAD-BEAM PLASMA APPARATUS



II

The Use of a Transmission Line Energy-Source With a Coaxial Plasma Gun

R. J. Gooding, B. R. Hayworth, A. V. Larson
NAS-3-2594
General Dynamics/Astronautics
San Diego, California

Previously reported experiments on the development of the coaxial plasma gun for space propulsion have indicated that an optimum energy-storage capacitor might have a capacity of approximately 20μfarads, an inductance of 1 nanohenry and be operated at about 10 kv. The conventional method of fabricating such an energy source is to parallel a large number of small capacitors on a coaxial transmission line.

In order to reduce the overall weight and size of the engine a single toroidal capacitor, 20μfarads, 3 nh, 10 kv was fabricated (illustrated in figures 1 and 2). With the coaxial gun operated in the gas triggered mode (for minimum load inductance) the capacitor acts as a distributed constant pulse-line with an impedance closely matched to the plasma. The current waveform, and the voltage waveforms at the breech of the gun and at the far end of the line, shown in figure 3, are exactly as one would predict from a transmission line model.

From these data we can determine the power input to the gun, and together with magnetic field measurements in the gun determine an energy balance for the system. The results show that approximately 88% of the initial stored energy had been deposited in the gun at t = 0.9μsecs, divided approximately equally between magnetic field energy and directed motion of the center of mass of the plasma. The

ohmic losses in the plasma apperar to be negligible.

This behaviour represents the closest approximation to an ideal coaxial rail gun that has been achieved in our program. Some of the consequences of the pulse-line mode of operation will be discussed.

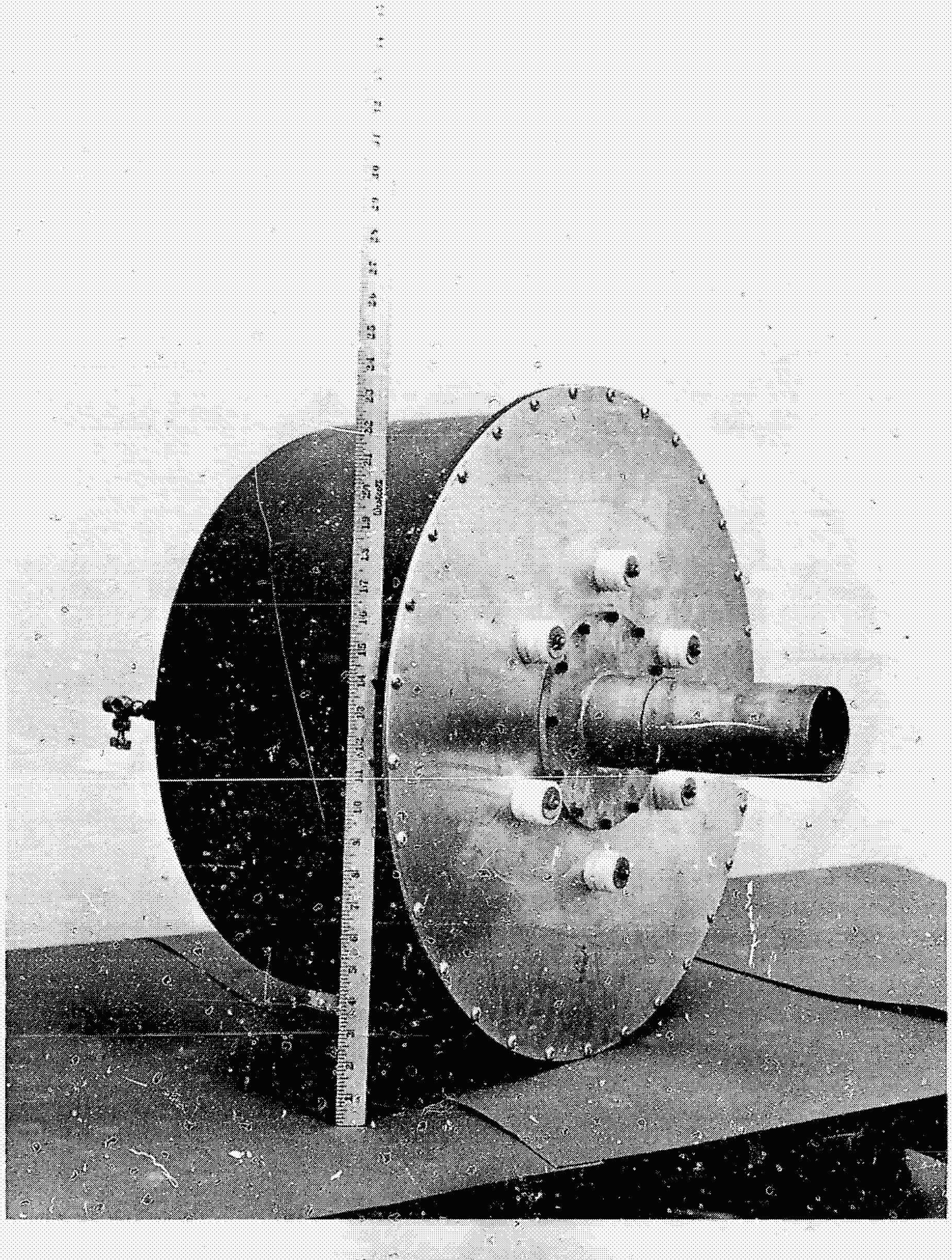


Fig. 1 Front View.

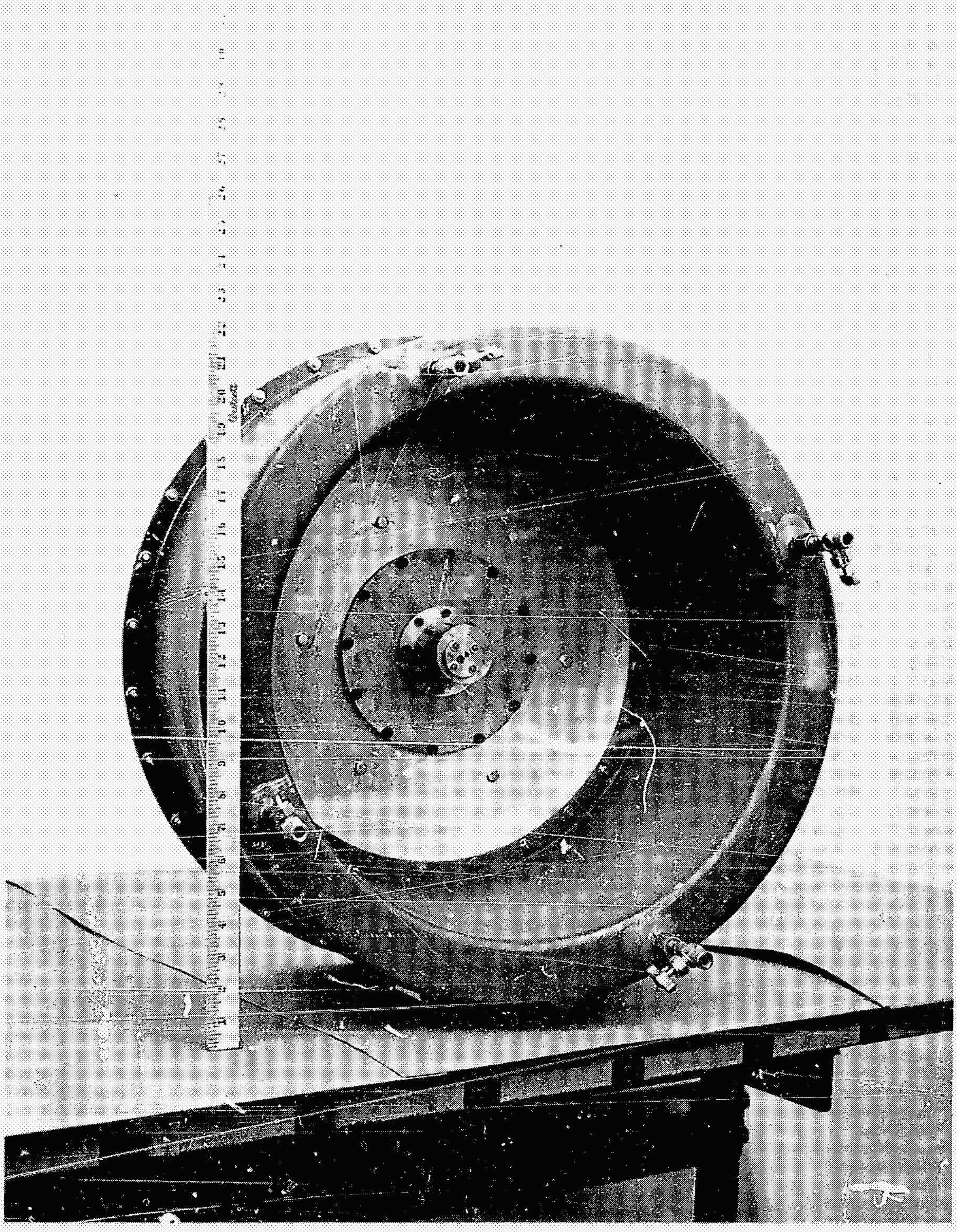
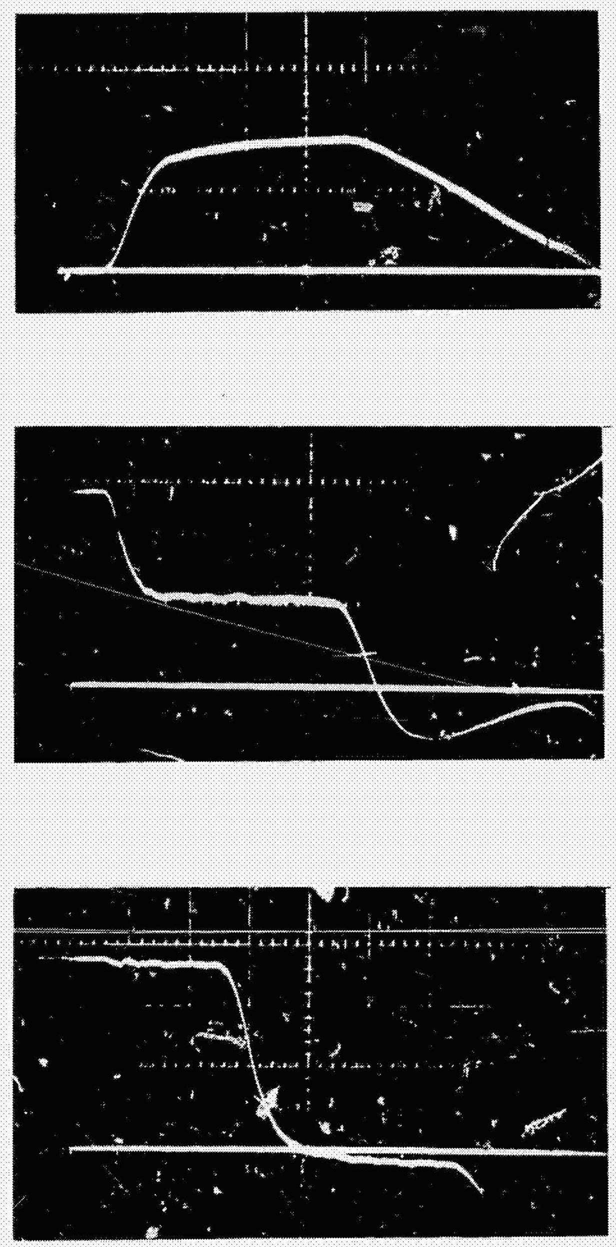


Fig. 2 Rear View.



CURRENT

VOLTAGE

VOLTAGE

I ~ 100,000 amps/cm , V ~ 2 kv/cm , t = 0.2 μsecs/cm .

Fig. 3 Current and Voltage Waveforms

II, 2

PERFORMANCE STUDY OF A REPETITIVELY PULSED TWO-STAGE PLASMA PROPULSION ENGINE

B. Gorowitz, P. Gloersen, J. H. Rowe
General Electric Company
King of Prussia, Pennsylvania
NAS 3-2502

This paper describes an investigation of the performance of a two-stage, repetitively pulsed plasma engine ultimately intended for prime propulsion in space. Prior to the time period covered by the present paper, a single-shot, single stage coaxial gun had been studied in considerable detail[1], leading to the concept of a two-stage repetitively pulsed engine. Subsequent data were obtained[2,3,4] on thrust as measured by a pendulum in the exhaust, collective velocities of the luminous species from streak camera and photomultiplier telescope records, and luminous species present in the exhaust on one particular two-stage accelerator configuration. In this paper, studies of individual luminous species present and their velocities will be described using accelerators which underwent successive design modifications. The chief objective of these modifications was to bring about reliable operation of the accelerator for reasonably long times over a wide range of power levels. Considerable success was achieved toward this end and sufficient information was obtained to permit design and construction of a refined version of the two-stage coaxial gun which was used in a more extensive series of performance measurements (e.g., thrust with a thrust balance and efficiency with a calorimeter).

The performance data obtained from thrust balance and calorimeter measurements to date, are summarized on Table 1.

REFERENCES

1. P. Gloersen, B. Gorowitz, and W. Palm, "Experimental Performance of a Pulsed Gas Entry Coaxial Plasma Accelerator, "Paper No. 1535-60 at the ARS 15th Annual Meeting, Washington, D. C., December 1960.

2. Per Gloersen, "Pulsed Plasma Accelerators", ARS Paper No. 2129-61, at the ARS Space Flight Report to the Nation in New York, October 1961.

3. B. Gorowitz, P. Gloersen, W. A. Hovis, Jr., "Experimental Studies of a Repetitively Fired Two-Stage Coaxial Plasma

Engine, "Paper No. 2377-62 at the ARS Electric Propulsion Conference, Berkeley, Calif., March 1962

4. P. Gloersen, B. Gorowitz, W. A. Hovis, Jr., and R. B. Thomas, Jr., "An Investigation of the Properties of a Repetitively fired Two-Stage Coaxial Plasma Engine," Paper No. 5 at the Flight Application Session of the Third Symposium of the Engineering Aspects of MHD, Rochester, New York, March 1962.

C ufd	V_c KV	$\frac{1}{2} C V_c^2$ Joules	P in Watts	T Newtons	$E_{terminals}$ Joules	$P_{terminals}$ Watts	$P_{calorimeter}$ Watts	η_{gun} $\frac{P_{cal.}}{P_{terminals}}$	I_{sp}/H sec.	$\dot{m}$ H K_g/sec.
15	9.0	607	6070	.0048	101	1010	120	11.8%	4900	0.96×10^{-7}
45	7.2	1160	2320	.0041	400	800	208	26.0%	10, 300	0.40×10^{-7}
45	9.0	1820	3640	.0085	641	1282	330	25.8%	7860	1.09×10^{-7}
45	10.0	2250	4500	.0182	791	1582	450	28.4%	4990	3.80×10^{-7}
45	12.0	3240	6480	.0342	1140	2280	988	43.5%	5830	6.00×10^{-7}

$$\nu = 2 \text{ sec}^{-1}$$

$$\dot{m}_{in} = 7.5 \times 10^{-7} K_g/\text{sec}$$

$$m_{eff.} = 0.024 \times 10^{-7} K_g/\text{sec}$$

$$H = \overline{v}^2 / \overline{v^2} = \frac{8}{3\pi} \text{ for Maxwelliam distribution}$$

Propellant - Nitrogen

Table 1 - Performance of the Two-Stage Coaxial Engine

II, 3

Operating and Exhaust Characteristics of a Coaxial Plasma Gun

C. J. Michels
NASA Lewis Research Center
Mountain View, California

Results of the single-shot-gun research program obtained subsequent to those reported in reference 1 are reviewed. A detailed study of the time history of the electrical parameters, power, and energy for the ignitron switched capacitor bank with inductive load (that is, a muzzle shorted gun) is described. This study was necessary to separate gun phenomena from bank characteristics.

An experimental investigation (reference 2) of the exhaust from a coaxial plasma gun (operated in crowbar mode) is discussed. Rogovsky loops at various stations, framing and streak cameras, and magnetic probes, were employed. The discharge appears first as a weak intensity diffuse plasma puff whose velocity as determined from the streak cameras is the same as the velocity of the current front as determined using magnetic probes. The location of the puff coincides approximately with the extrapolated current front location. A short time later, an intense, well-collimated and elongated luminous core appears from the tip of the inner electrode. The velocity of the leading edge of this core is slightly less than the current front. Loop measurements indicate that the core is part of a closed current path between inner and outer electrode and is current carrying well downstream of the gun.

The operation of gun configurations with various electrode geometries is examined. The initial discharge location was found to be at the gas

ports. Moving the gas ports to the breech has resulted in utilization of the full length of the gun barrel for acceleration as noted by magnetic probe traces.

To reduce bank cable losses and permit higher gun currents, the bank transmission line cables have been redesigned and modified. The results of a gun performance survey using the modified bank are presented.

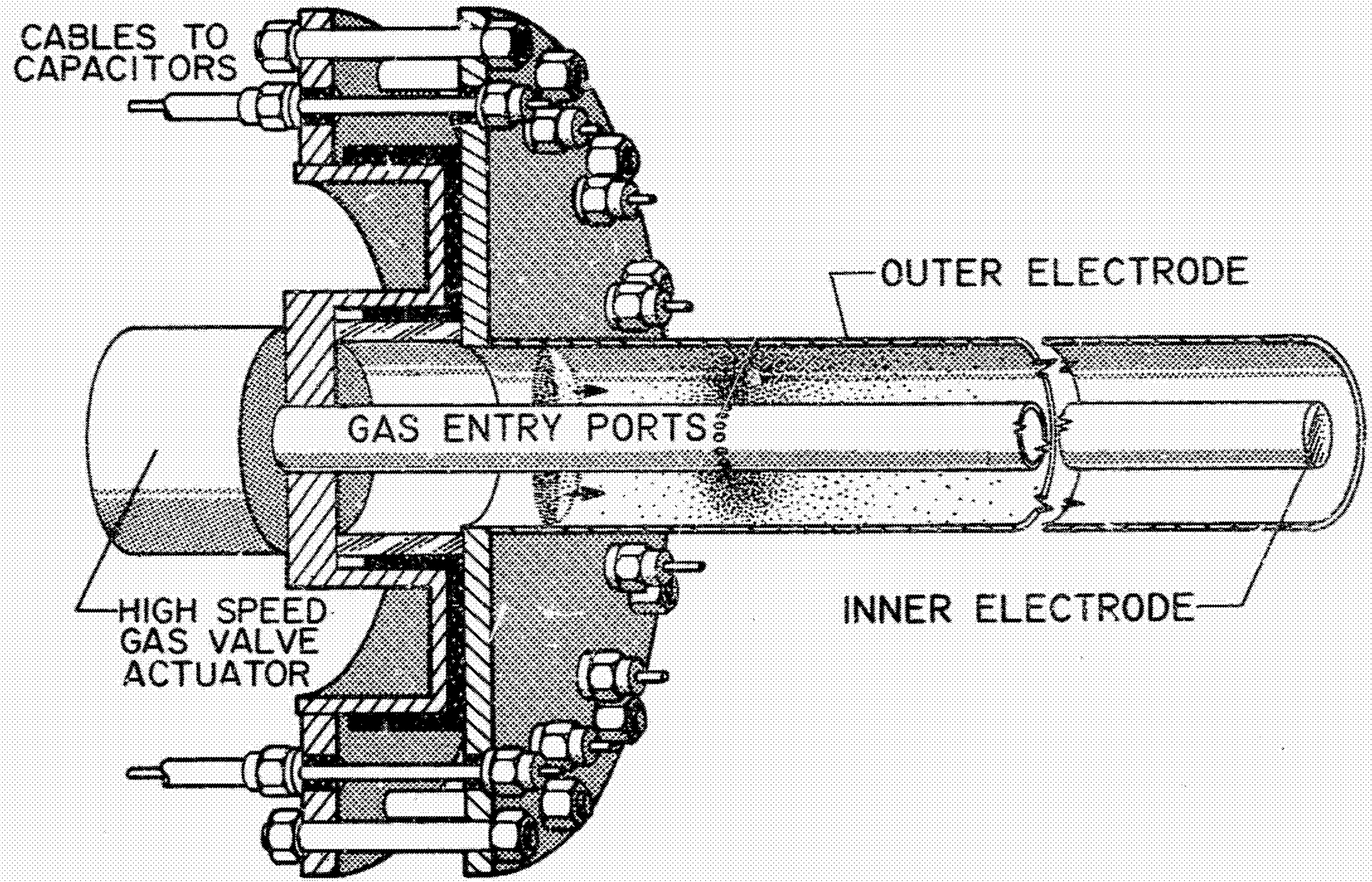
References:

1. Michels, C.J. and Ramins, Peter, "Performance of Coaxial Plasma Gun With Various Propellants." Presented at International Coaxial Plasma Gun Symposium, Case Institute of Technology, Cleveland, Ohio, September 6-7, 1962. To be published in Special Issue of Physics of Fluids compiling the Symposium papers.

2. Michels, C.J., "Study of Coaxial Plasma Gun Exhaust." Bul. of Am. Phys. Soc., 441, (1963).

NASA
CS-25624

COAXIAL PLASMA GUN



II, 4

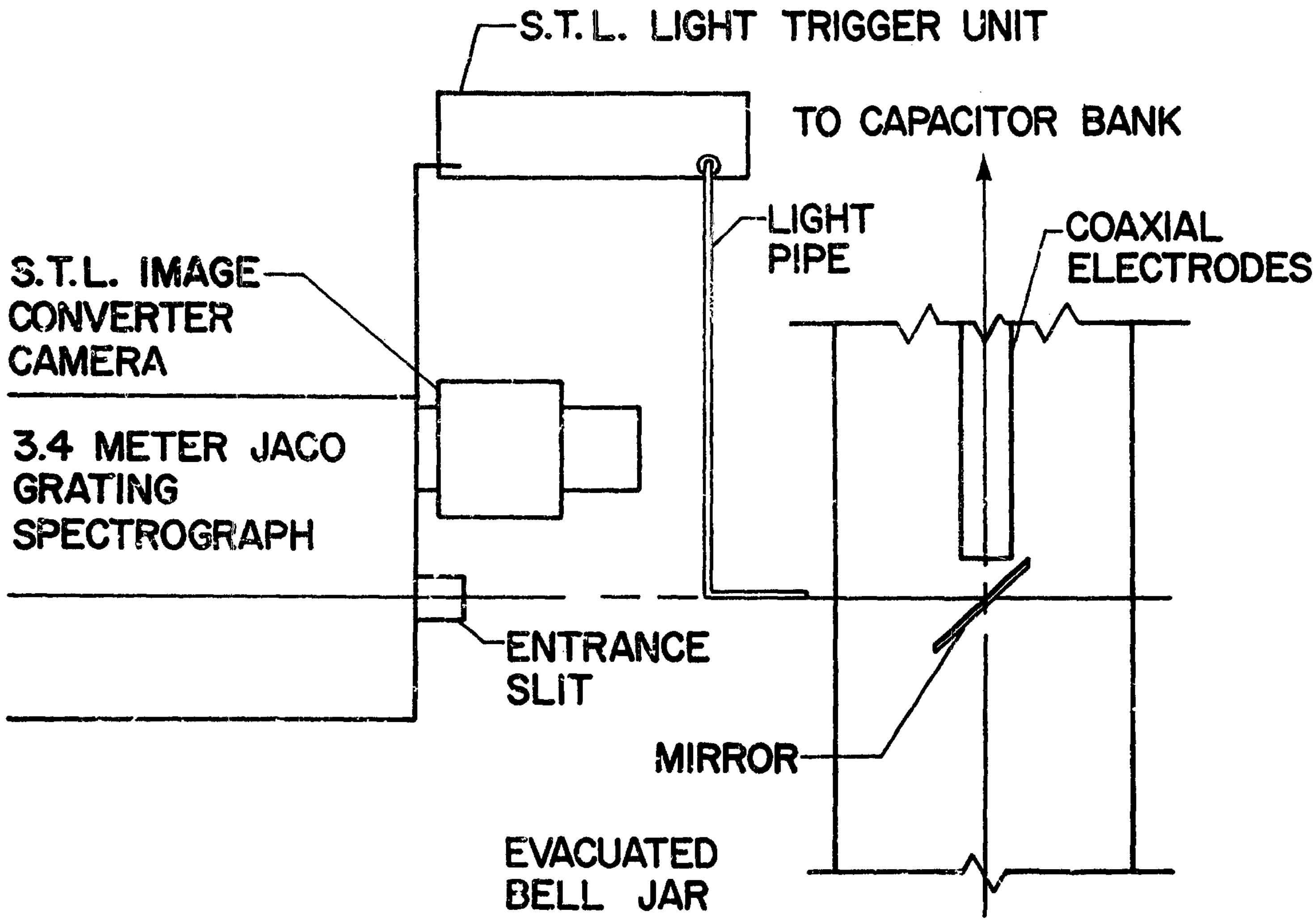
Spect· · ·pic Observations on a Pulsed Coaxial Plasma Gun and Radia· ·osses from Plasmas Consisting o· High Z Materials

G. Oertel, N. Jalufka and J. Norwood
NASA Langley Research Center

1. Electromagnetic radiation from the p·asma in a pulsed coaxial plasma gun had been observed with some space and time resolution, by use of a stigmatic spectrograph and an image converter camera. The plasma concists mostly of electrode material at estimated electron temperature and density of $35000^{o}K$ and several times 10^{16} per cm^3, respectively, downstream just beyond the nozzle. The plasma between the electrodes is most luminous near the inner electrode, where a strong continuum with absorption lines is observed during the first few microseconds after the formation of the discharge. Later these absorption lines turn into emission with an accompanying considerable drop in total light intensity. If the plasma were a blackbody at about $60,000^{o}K$, about one hundred joules per cm^2 per microsecond would be radiated away, mostly in the vacuum ultraviolet and soft x-ray regions of the spectrum. Bound-bound and free-bound electron transitions may account for a photon mean free path which is much shorter than the plasma dimensions. Direct measurements of the loss in the far vacuum ultraviolet are in progress and could shed light on the energy balance in some plasma accelerators.

2. Experiments indicate the emission of blackbody radiation in the visible region of the spectrum from a hot plasma consisting mainly of materials of large nuclear charge. The calculation of the absorption

coefficient for nonhydrogenic ions is difficult, because it depends upon transition probabilities, broadening parameters, and nonthermal populations of ionic states. It can be estimated, however, that such plasmas tend to become optically thick over a wide range of wavelengths at moderately high temperatures ($\sim$5 eV). The consequence would be a high energy loss as radiation, mostly in the vacuum ultraviolet region of the spectrum, which may affect the figure of merit of some plasma accelerators and may provide a strong pulsed source of vacuum ultraviolet radiation.

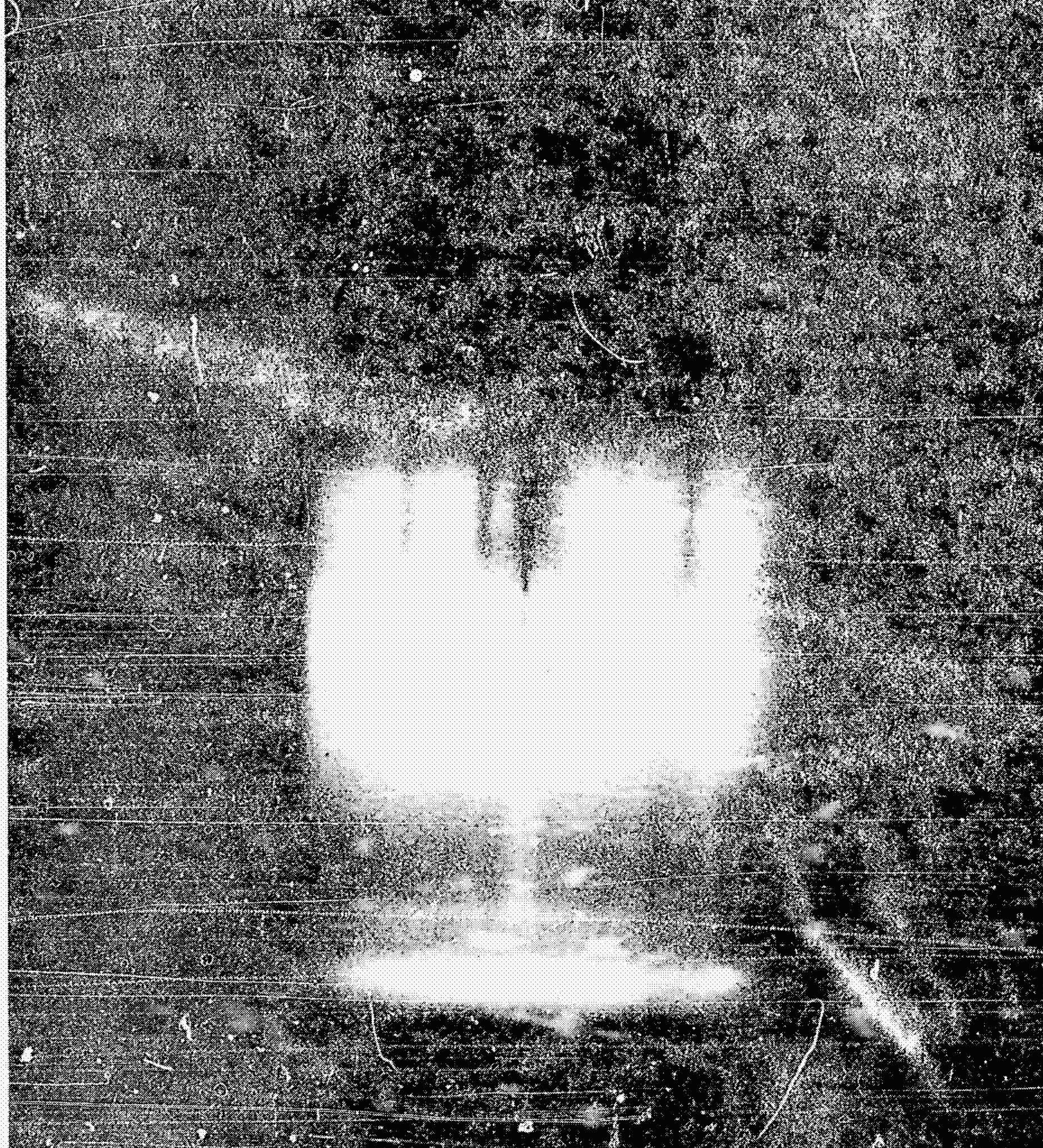


SPECTROSCOPIC OBSERVATIONS ON PULSED COAXIAL PLASMA GUN

I Experimental Set-up

SPECTROSCOPIC OBSERVATIONS ON PULSED COAXIAL PLASMA GUN

II Space Resolved Spectrum of Down-Stream Plasma



SPECTROSCOPIC OBSERVATIONS ON PULSED COAXIAL PLASMA GUN

III Time Resolved Spectrum in Electrode Region showing Continuum, Absorption and Emission Lines.

II, 5

Radiation from High Temperature Plasmas

A.C. Kolb
NASA Contract R-9
U. S. Naval Research Laboratory
Washington, D. C.

Just as in stellar atmospheres, the radiation emitted from high temperature laboratory plasmas is characteristic of the state of the gas. The problems associated with determining the density, temperature, composition, as well as heating and energy loss mechanisms, are common to both astrophysics and plasma diagnostics.

Because of certain scaling laws between density, ionic charge, ionization potentials and temperature, the atomic collision processes and radiation phenomena in low density stellar atmospheres may be studied directly at higher densities.

High current θ-pinches and electromagnetic shock tubes can be used to produce electron temperatures from about 10^4 °K to 10^7 °K. Such sources produce radiation throughout the soft x-ray, vacuum ultraviolet and visible regions of the spectrum.

Shock tube experiments have progressed to the point where densities can be measured to better than 10%, while temperatures may be determined in many cases to within 1.5 to 5%, depending on the particular circumstances. The various diagnostic methods, their precision and current problems will be reviewed.

With the development of fairly precise spectroscopic techniques it is now possible to measure f-numbers and damping constants of spectral

lines of astrophysical interest. The experimental possibilities in this area are only beginning to emerge, particularly in the ultraviolet region which has recently assumed great importance, courtesy of satellite and rocket observations.

Above about 5ev shock tubes have not yet proven reliable as light sources. However, plasmas with temperatures over 10ev and as high as 100ev can be reproducibly generated by magnetic compression in a Θ-pinch. Fields up to $\sim$100KG thermally isolate the plasma for times of 10-30μsec in the largest NRL experiment. Discharges in 2m coils with currents up to 14MA from a 1.4MJ capacitor bank are presently under investigation. Some of the problems associated with operating such devices to produce stable discharges will be summarized.

Despite the complexity of the hydromagnetic processes, it is possible to solve the full nonlinear two-fluid (ions and electrons) equations for the Θ-pinch geometry. This provides a "model atmosphere", analogous to those used for stellar atmospheres, on which to base an analysis of the radiation emitted by the plasma. Calculations will be discussed in which the rate equations for ionization are solved simultaneously with the hydromagnetic equations. In this way the temporal and spatial distribution of ionic species is obtained. Free electrons collide with the ions and raise the bound electrons to excited levels from which they decay with the emission of line radiation. Because of the high temperatures in a Θ-pinch, the Corona model is valid so that the intensity of vacuum ultraviolet spectral lines is proportional to the excitation rates.

The goal of these studies is to calculate from first principles, utilizing the best available cross-sections, the spectrum of high temperature plasmas. A detailed comparison between theory and experiment should be very instructive for the interpretation of satellite spectra.

In addition to the problems outlined above, work on the identification of UV spectral lines, absolute calibration of spectrographs, and theoretical spectroscopy will be mentioned.

Spectral Line Intensities Emitted By Optically Thin Plasmas

G. K. Oertel and M. T. Raiford
NASA Langley Research Center
Hampton, Virginia

In optically thin plasmas radiative transitions are not balanced by their respective reverse processes which may lead to deviations from thermodynamic equilibrium. If one desires to apply the Fowler-Milne method for determining electron temperatures from spectral line emission, one must correct the usual Saha equations and Boltzmann factors. Elwert's corona equations and approximate semi-corona equations were used independently and the results compared to the ordinary thermodynamic equilibrium case. The regions of observability of spectral lines were determined by comparison to the continuum. Line intensities were calculated as functions of electron temperature and density for highly ionized atoms. Partition functions were neglected.

II, 7

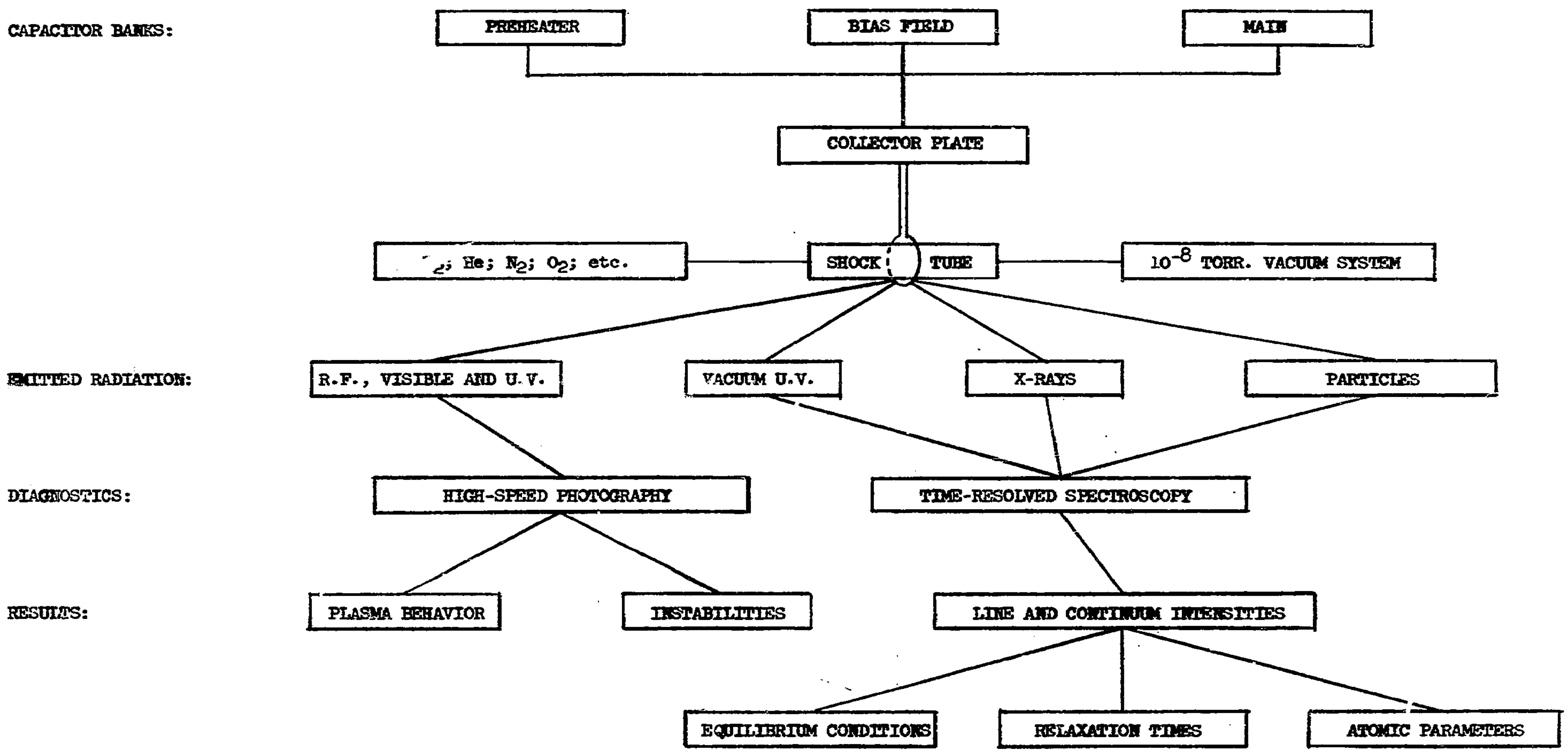
Magnetic Compression Experiment

G. K. Oertel
NASA Langley Research Center
Hampton, Virginia

The construction of a magnetic compression experiment is well underway. Some of the problems encountered will be discussed in relation to the projected use for the study of radiation emitted by highly ionized atoms under conditions which are similar to those in the solar corona. While the density is much higher than in the corona, similar equilibrium conditions prevail, and determinations of cross sections and transition probabilities would also be useful.

The main capacitor bank has a capacitance of 5000μF and stores one megajoule of electric energy which may be discharged at 20 kilocycles per second through a load of 10 millimicro-henries, giving rise to a peak current of 12 million amperes. A preionization bank and a slow bias bank are also being planned.

MAGNETIC COMPRESSION EXPERIMENT



CAPACITOR BANK PARAMETERS

	PREHEATER	BIAS FIELD	MAIN	UNITS
CAPACITANCE	9	10^3	5×10^3	Microfarads
ENERGY STORAGE	2	70	1000	KJoules
OPERATING VOLTAGE	20	12	20	KVolts
COIL VOLTAGE	6	.3	16	KVolts
FREQUENCY	300	10	20	Kcycles/sec
PEAK CURRENT	350	700	1.2×10^4	KAmps

COIL INDUCTANCE: 10^{-8} Henries

II, 8 Pulsed Electromagnetic Gas Acceleration

R. G. Jahn and W. von Jaskowsky
NsG-306-63
Princeton University
Princeton, N. J.

The purpose of this project is to acquire a more complete understanding of the various physical phenomena which participate in pulsed electromagnetic gas accelerators. Specifically, the research involves systematic experimental and theoretical studies of the initiation, development and dynamic progress of the current sheets, associated magnetic field fronts, and the gasdynamic waves they drive, in various large-radius pinch discharges. The discharges are generated in a variety of cylindrical chambers each composed of a pair of plane circular aluminum electrodes, from 4 to 8 inches in diameter, separated by a 2-inch gap of test gas. Concentric external banks of capacitors, charged to 10KV, are switched across those gaps through low inductance circuits which ring down at about 250 KC (see Figure 1). Each discharge is observed to initiate as a uniform peripheral ring of luminous gas at the outer edge of the electrodes, and then to pinch itself radially inward at speeds up to 10^5 m/sec, depending on ambient pressure, gas type, chamber radius, and external circuit parameters. Subsequent discharges, occurring at the second, third, and later maxima of the capacitor ring-down pattern, also are established at the outer edge of the electrodes, and follow the primary pinch into the center.

The development of the breakdowns and implosions within these discharges are studied by a variety of diagnostic techniques. Rotating mirror streak photographs provide a complete history of the luminous

events along a diameter of the pinch chamber (see Figure 2). Kerr-cell single frame photographs examine the azimuthal symmetry of the discharges at selected times during their development (see Figure 3). Electric and magnetic probes and a microwave reflection interferometer provide information on the distribution of charge, current and interior magnetic fields accompanying these luminous fronts, while a voltage divider and Rogowski coil monitor the current and voltage excursions on the electrodes. Photo-electric spectroscopy follows the development of the concentration of the various atomic and ionic species throughout the discharge processes.

Without exception, these experiments reveal a high degree of reproducibility and symmetry in this type of discharge. The cylindrical luminous rings are found to be azimuthally stable throughout their inward excursion, and the response of any interior probe at a given position is normally identical from shot to shot. The quantitative experimental results are compared with relevant theoretical formulations of the particular processes involved. For example, from the space and time variations of the interior magnetic fields determined by the magnetic probe experiments, the concommitant distributions of current densities within the discharge are evaluated. These are found to be localized in concentric cylindrical sheets which, like the luminous fronts, propagate radially inward from the periphery of the electrodes. The observed radius-time trajectories of these sheets have been compared with theoretical snow-plow calculations, and are found to be reconcilable if some fractional "sweeping efficiency" is assigned to each of the observed current sheets. This empirical sweeping efficiency varies from 10% to 100%, depending on

the initial pressure, the radius of the discharge, and the level of ambient ionization ahead of the current sheet. Independent estimates of sweeping efficiency can be made from the comparison of the luminous front trajectories with those of the current sheets, and these qualitatively confirm the empirically selected values. In a related series of experiments, the applicability of the scaling laws implicit in the snow-plow formulation has been explored experimentally by changing the initial pressure, the type of gas, the radius of the discharge, the capacitance of the external bank, and the inductance of the external circuit.

Certain unanticipated phenomena have been observed in the course of these studies, but not yet identified. For example, a precursor front is found to propagate radially inward at several times the speed of the first luminous front, slightly ionizing the ambient gas prior to the arrival of the first current sheet. Detailed microwave probing of these fast precursors (2×10^5 m/sec) is in progress.

The future course of the program involves the extension of studies similar to those outlined above to discharge circuits of very low external inductance, to other discharge geometries, and to discharges with exit orifices.

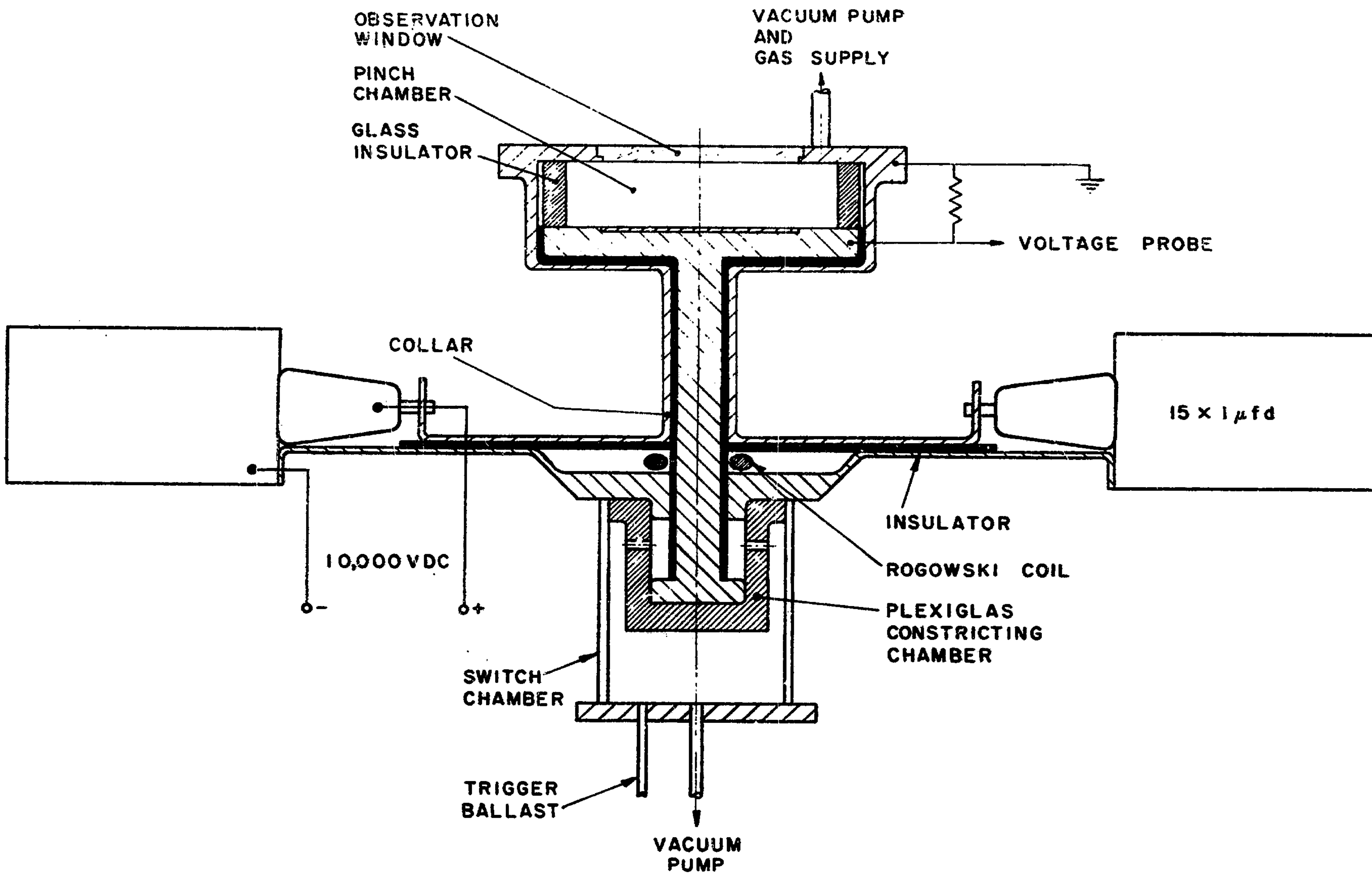
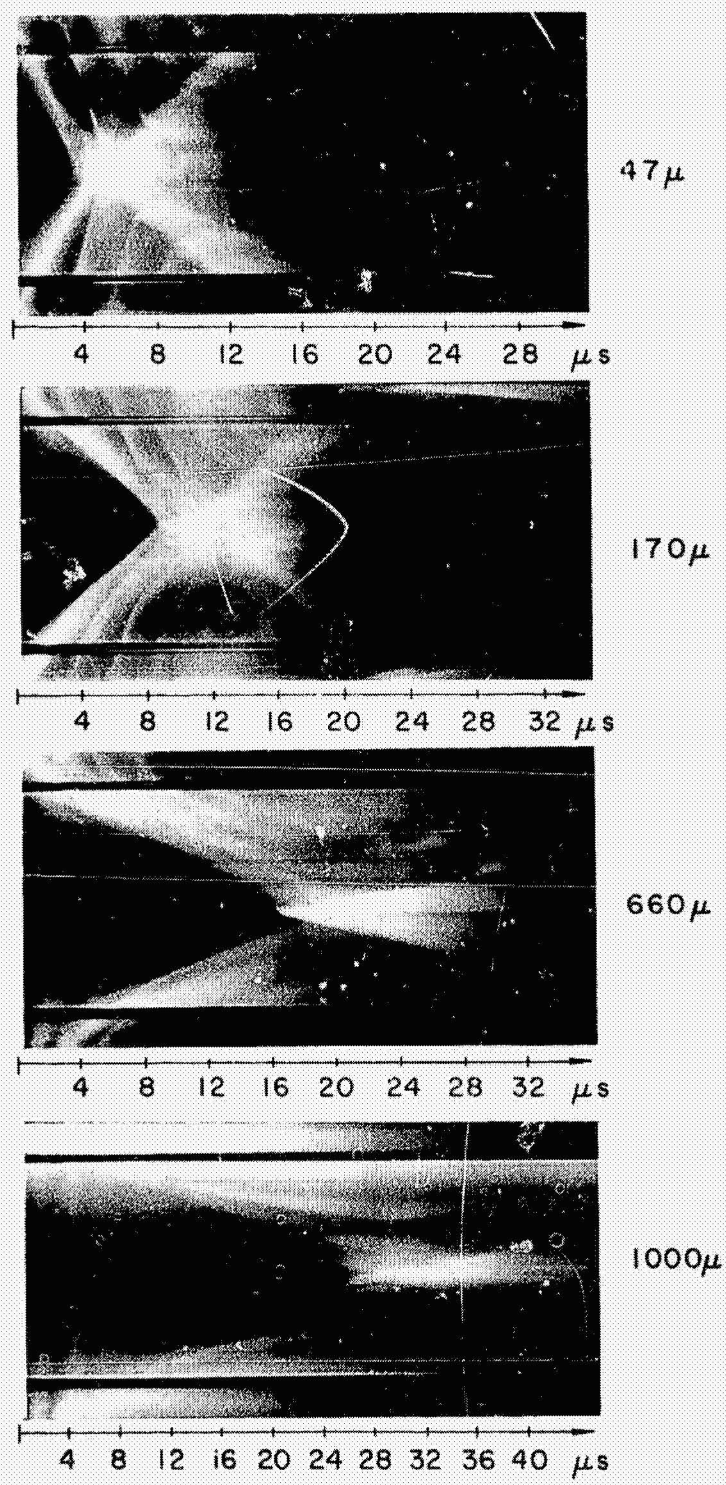
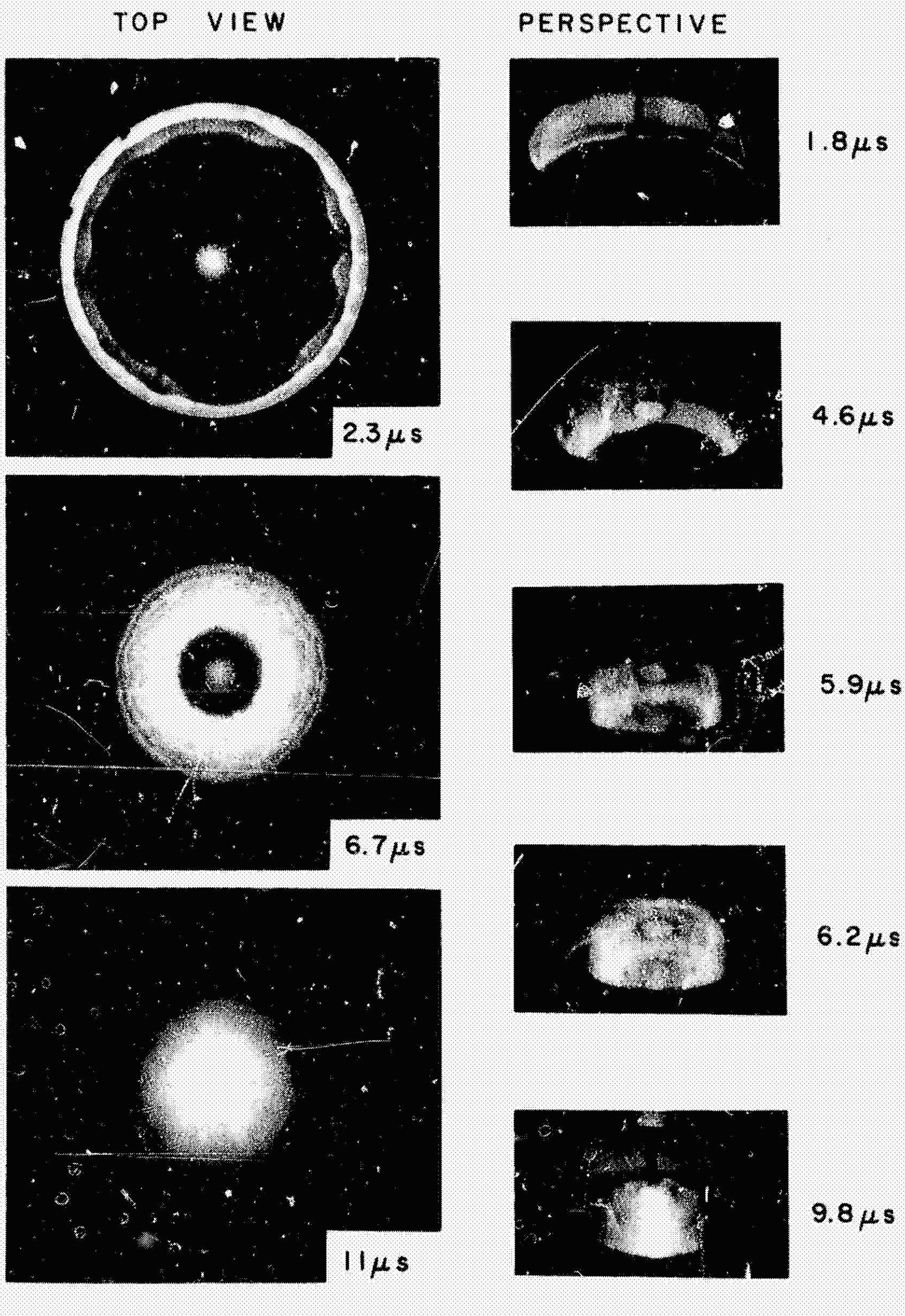


FIGURE 1. PLASMA PINCH APPARATUS (SCHEMATIC)



STREAK PHOTOGRAPHS OF PINCH DISCHARGE IN ARGON

FIG. 2



AXIAL PHOTOGRAPHS OF PINCH DISCHARGE

170 μ ARGON; 0.05 μ SEC EXPOSURE.

FIG. 3

II, 9

MEASUREMENTS OF HIGH-ENERGY PLASMAS IN UNDERWATER SPARK CHANNELS AT 10^5 ATMOSPHERES

J. W. Robinson
H. C. Early
The University of Michigan
Ann Arbor, Michigan
NsG 415

A high-pressure, high-density plasma can be produced, on a transient basis, by an underwater spark discharge. The confining pressure on the underwater spark channel can be greatly increased if the water is pre-compressed by a chemical explosive before the spark discharge is initiated. This investigation uses PETN explosive to produce a transient water pressure of approximately 10^5 atmospheres with a time duration of approximately 2 microseconds. All of the measurements on the spark-produced plasma will be taken during this 2-microsecond interval.

Experimental measurements will be made of the pressure, temperature, energy density, and conductivity of the plasma. The pressure in the plasma depends both on the pressure in the water due to the PETN explosive and the additional confining pressure on the spark plasma due to the inertial restraint of the water on the expansion of the spark channel. Calculations of the pressure in the water due to the explosive are based on a shock velocity measurement, while calculations of the inertial confinement pressure on the channel are based on the rate of channel growth obtained by Kerr Cell photography. Temperature measurements are based on black-body radiation intensity in the optical spectrum. Energy density is calculated from the electrical energy input, channel size, mechanical energy loss because of channel expansion, and radiative energy loss.

This present program is an extension of previous University of Michigan research on underwater sparks by E. A. Martin in which plasma pressures of 10^4 atmospheres were produced by the inertial restraint of surrounding water on the expanding spark channel. The gas in the channel had a density of 2×10^{21} particles per cm^3 and 30% ionization at a temperature of 3×10^4 °K. The peak current was 85,000 amperes with a rise time of 2 microseconds. The present experiments using a chemical explosive and a faster rate of current rise are expected to produce plasma pressures and temperatures at least

an order of magnitude larger. A library survey indicates that laboratory measurements in this region of pressure and temperature have not previously been reported in the literature.

The analysis of the data to be obtained on the present program will involve corrections to Saha's equation necessitated by the unusually high particle density which will be of the order of 10^{22} particles per cm^3. A correction due to quantum degeneracy of the electrons may be obscured by other effects such as the lowering of ionization potentials. Calculations of plasma conductivity will be compared with experimental data. Calculations of magnetic pinch pressure indicate that significant radial pressure gradients may exist inside the cylindrical spark channel, particularly in experiments where the spark current has a very fast rate of rise. In this case "sausage" type of pinch instabilities are expected to be present.

III, I THE SHAPE OF AN ELECTRIC ARC IN AN ANNULAR GAP AND AN AXIAL MAGNETIC FIELD

J. R. Jedlicka
NASA Ames Research Center
Mt. View, California

An equation is derived for the mathematical curve of an electric arc taking place between coaxial, coplanar electrodes submerged in a uniform axial magnetic field. The geometry is that of some large arc heaters. This three-dimensional MHD problem is attacked by making simplifying assumptions, the principal one being to replace the arc by a flexible, solid rod conductor. The resulting curve is an involute, and comparison with experimental photographs is good. The implication of the involute shape on the evidence for the existence of a "diffuse discharge" is discussed.

III, 2 THE CYLINDRICALLY CONSTRICTED D. C. THERMAL ARC WITH AXIAL AIR FLOW - A COMPARISON OF THE SIMPLIFIED THEORETICAL MODEL WITH EXPERIMENTAL RESULTS

V. R. Watson
NASA Ames Research Center
Mt. View, California

Recent experimental work by Shepard is compared with the simplified, theoretical model proposed by Stine and Watson of Ames for the constricted thermal arc with an axial flow of air and with negligible radiation losses. Numerical calculations for the thermal arc with appreciable radiation losses are also presented.

Measurements were made of the average enthalpy, voltage gradient, and heat flux of the gas as a function of the axial position within the cylindrical throat of a constricted-arc plasma generator. One generator with a 1/4" diameter constrictor, and one generator with a 1/2" diameter constrictor were tested at stagnation pressures ranging from 1/3 to 2 atmospheres. The experimental measurements of the arc characteristics agree qualitatively with the characteristics predicted by the simplified model.

Numerical solutions of the Elenbaas-Heller equation wich include the effect of radiation losses on the thermal arc are discussed. A method is presented for approximating the characteristic constrictor length required for the gas enthalpy to approach its maximum with an axial flow of gas under conditions where the radiation loss is appreciable. Increased radiation loss flattens the radial enthalpy profile of the arc column and shortens the characteristic length.

III, 3

DESCRIPTION OF A SEEDED GAS PLASMA FOR A LOW DENSITY WIND TUNNEL

W. Christiansen
Jet Propulsion Laboratory
Pasadena, California

An experiment with ionized gases has been initiated in the JPL low-density wind-tunnel facility. A plasma source has been constructed utilizing thermal ionization at moderate temperatures (2000°K - 3000°K) by seeding argon gas with cesium. It is expected that the flow will be more uniform and controllable than that produced in conventional arc jet tunnels. Hopefully the neutral seed element is nothing more than a passive contaminant in all aerodynamic problems to be considered. The essential component of this system is the heat exchanger. It has been designed using graphite as the primary element of construction, with a novel system of a resistance-heated helical element and adiabatic stagnation chamber, resulting in a compact arrangement.

With only moderate power requirements (8000 watts), the heat exchanger can operate up to 3000°K. It was found that the gas temperature is effectively the heater temperature. The heater has shown reliability and a reasonably long life even when using cesium. Preliminary Langmuir probe measurements for one particular condition of operation indicate that the ion number density and electron temperature seem to be slightly larger than that indicated by the Saha equation and heater temperature, respectively.

III, 4 HEAT TRANSFER FROM IONIZED ARGON

P.F. Massier
Jet Propulsion Laboratory
Pasadena, California

This investigation was initated as a result of general interest in MHD propulsion concepts and the recognition that containment of ionized gases ranging in temperature from 2,000 to 15,000 °K may pose some critical cooling problems in these devices. Although the study was initiated as a result of device concepts, the ultimate goal is to obtain an understanding of heat transfer phenomena. Because of the complications imposed upon the overall heat transfer process by the very nature of an ionized gas, preliminary experimental and analytical studies were initiated without having introduced the added complexity of an applied magnetic field.

Experimental heat-flux distributions have been obtained by calorimetry from ionized argon flowing through various configurations of axisymmetric anodes, mixing chambers, convergent-divergent nozzles and diffusers located downstream of an arc-jet into which the argon was injected tangentially. At the nozzle inlet average ionization fractions based on an energy balance have ranged up to approximately 0.23; stagnation temperatures ranged between 6,400 and 12,600 °K and stagnation pressures ranged between 1.5 and 29 psia. For one test in which the ionization fraction was 0.228 the experimental heat-flux distribution is used as a nozzle-wall boundary condition to predict the average one-dimensional flow variables along the nozzle. It is assumed that the flow through the nozzle is frictionless and that the atom, ion and electron temperatures are equal. Both equilibrium and nonequilibrium cases are considered.

A thin laminar equilibrium boundary-layer approach is investigated as a possible method to predict the convective heat transfer to the nozzle wall. Two analysis are considered: one in which $C = \rho\mu/\rho_e\mu_e = 1$ throughout the nozzle and the other in which C is allowed to vary along the nozzle with $\rho\mu$ evaluated at a reference temperature. A dimensionless heat-flux parameter is obtained which is used as a basis for comparison with experimental data. Comparisons are made only with those tests in which the ionization energy was less than 10% of the total energy content of the gas since in these analyses the effects of ionization were neglected. Furthermore, the contributions to the heat transfer resulting from radiation and swirl were assumed to be small even though these effects were present during the tests. The trends of the predictions based on C varying along the nozzle are in better agreement with test results for one of the nozzle configurations than when C = 1. For another nozzle configuration the reverse is true.

III, 4

To account for some of the ionization effects on the heat transfer to the nozzle wall the additional energy transfer due to mass diffusion by ion-electron pairs and atoms is also considered in another analysis. As an initial appraisal of these effects simplifying assumptions are made which allow analytical solutions to be made. Two limiting cases are investigated for which the composition in the nozzle core is considered to be frozen. In one case the net production of electrons was assumed negligible compared to diffusion through the boundary layer by electron-ion pairs. In this case the predicted total energy transfer to the wall is below that predicted by neglecting ionization effects. In the other case for which local equilibrium was assumed in the boundary layer a negligible effect on energy transfer resulted because of the cold wall.

Future experimental activities are discussed in which additional diagnostic methods and test apparatus configurations will be used.

III, 5

DISCHARGE, ACCELERATION, DIFFUSION AND RECOMBINATION IN PLASMA FLOWS SUBJECTED TO STEADY APPLIED FIELDS

G. R. Russell
Jet Propulsion Laboratory
Pasadena, California

The overall long range objective of the research program conducted in the Magnetogasdynamics Group at JPL is to contribute to the understanding of the basic phenomena that govern the behavior of partially ionized gases flowing under the influence of steady applied electromagnetic fields. A summary of the existing program is presented. In particular the following projects are discussed:

1. Parametric cross-field plasma flow study.
2. Electrode blowing with applied magnetic fields.
3. Study of breakdown phenomena in partially ionized gases with applied magnetic fields.
4. Spectrochemical analysis of binary gas systems.
5. Study of magnetogasdynamic shock structure in non-equilibrium flows with applied magnetic fields.
6. Measurement of electron recombination rates.
7. Anomalous plasma diffusion study.

Preliminary experimental data is presented from the anomalous diffusion study. The performance of a single stage, constant pressure cross-field accelerator is described showing velocity and electron density profiles in the accelerator exhaust and the overall thermal efficiency obtained by calorimetry.

III, 6

TRANSPORT EQUATIONS FOR A PARTIALLY IONIZED GAS IN AN ELECTRIC FIELD

P. M. Sockol
NASA Lewis Research Center
Cleveland, Ohio

Transport equations for a partially ionized gas in an electric field are derived from the Boltzmann equation by the Grad 13 moment method. Charged particle interactions are described by Coulomb forces while all other particle interactions are described by a rigid elastic sphere model. First approximations to currents, stresses, and heat fluxes are obtained. The resulting transport relations are suitable for use in situations where the electrons have an elevated temperature.

III, 7 THEORY OF NON EQUILIBRIUM FLOWS IN CROSSED ELECTRIC AND MAGNETIC FIELDS

G. R. Russell
Jet Propulsion Laboratory
Pasadena, California

The generalized macroscopic equations describing the flow of a three-component compressible plasma with different specie temperatures in an electromagnetic field, are solved on an electronic computer to describe the non-equilibrium flow in applied crossed electric and magnetic fields. Both accelerated and decelerated argon and helium flows are studied. In addition to the generalized tensor electrical conductivity, radiation, diffusion, thermal conduction, and finite rate phenomena are included in the analysis.

Two limiting cases are studied. One deals with the changes in plasma properties perpendicular to the flow and parallel to the applied electric field. The second case includes the changes in plasma properties in the direction of the flow, perpendicular to both the applied electric and magnetic fields.

Preliminary results with argon indicate that at pressures of the order of 1 mm Hg, the plasma is forced far from equilibrium by the applied electromagnetic field. The electron temperature is raised considerably above the atom temperature, and the degree of ionization is several orders of magnitude higher than it would be at equilibrium with the atom temperature.

The degree of equilibrium attained in acceleration of the plasma does not have a dominant effect on the amount of acceleration attained with a given electromagnetic field, nor on the overall efficiency of the acceleration process, provided the plasma approaches the drift velocity induced by the electromagnetic field. However, the degree of attainment of equilibrium is dominated by the applied electromagnetic field so that accelerated or decelerated plasmas can be used as sources for experiments such as an electron recombination study where the plasma properties must be systematically varied over a wide range of pressures and temperatures.

III, 8

NONEQUILIBRIUM IONIZATION IN THE PRESENCE OF ELECTRIC AND MAGNETIC FIELDS

H. A. HASSAN

North Carolina State University
Raleigh, N. C.

NsG 363

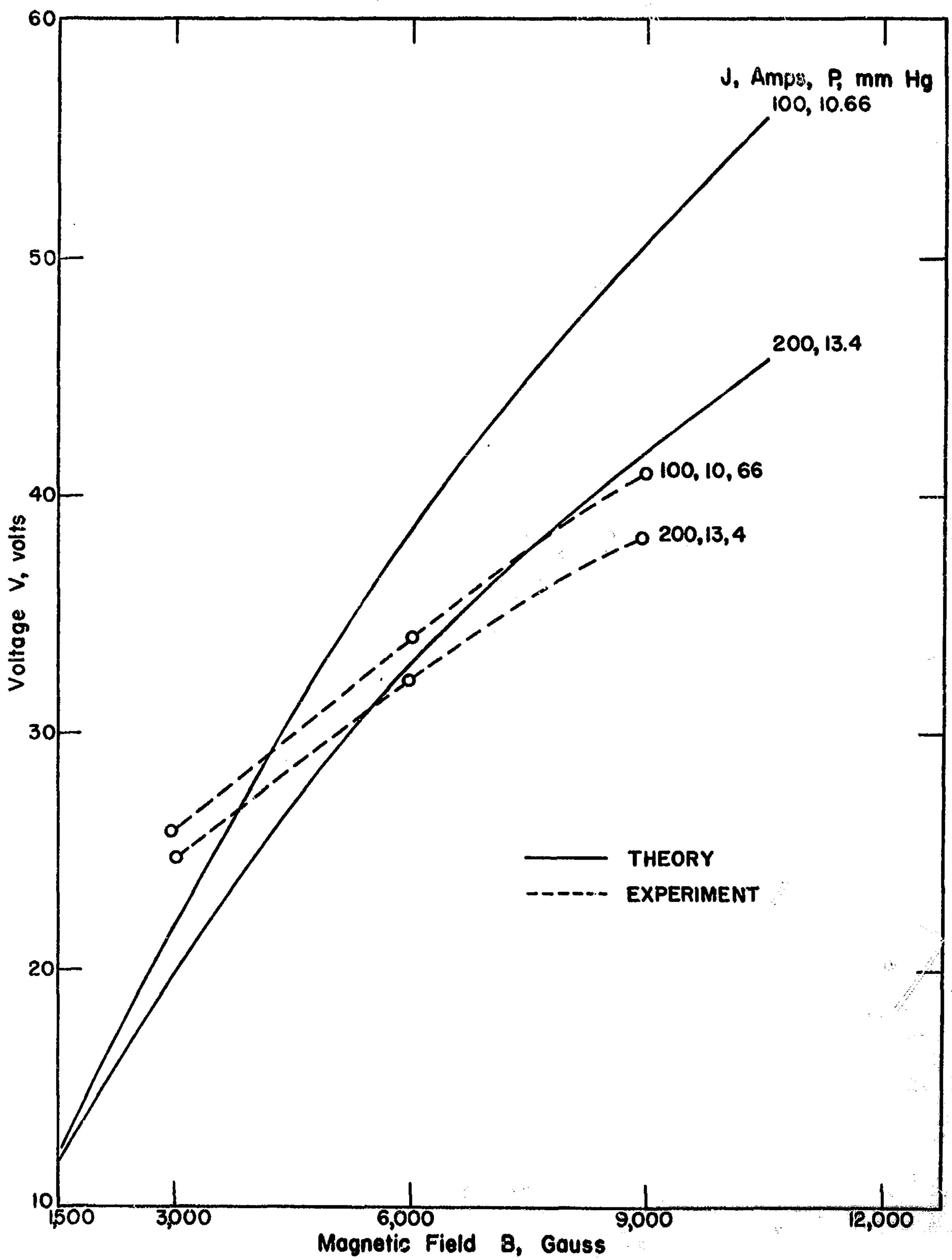
The study deals mainly with an evaluation of plasma accelerators which combine the arc jet and the accelerator in one package. Before outlining the procedures that have been developed to analyze such devices, a brief review of their features will be given.

By combining the arc jet with the accelerator one can take advantage of the phenomenon of nonequilibrium ionization in arc discharges. In this phenomenon the electric field raises the electron temperature to a value much higher than the gas temperature, thus enabling one to attain high degrees of ionization, through the electron-neutral collisions, at reduced gas temperatures. Thus, in addition to raising the electrical conductivity, nonequilibrium ionization may be the key for overcoming the materials problem resulting from the high gas temperature.

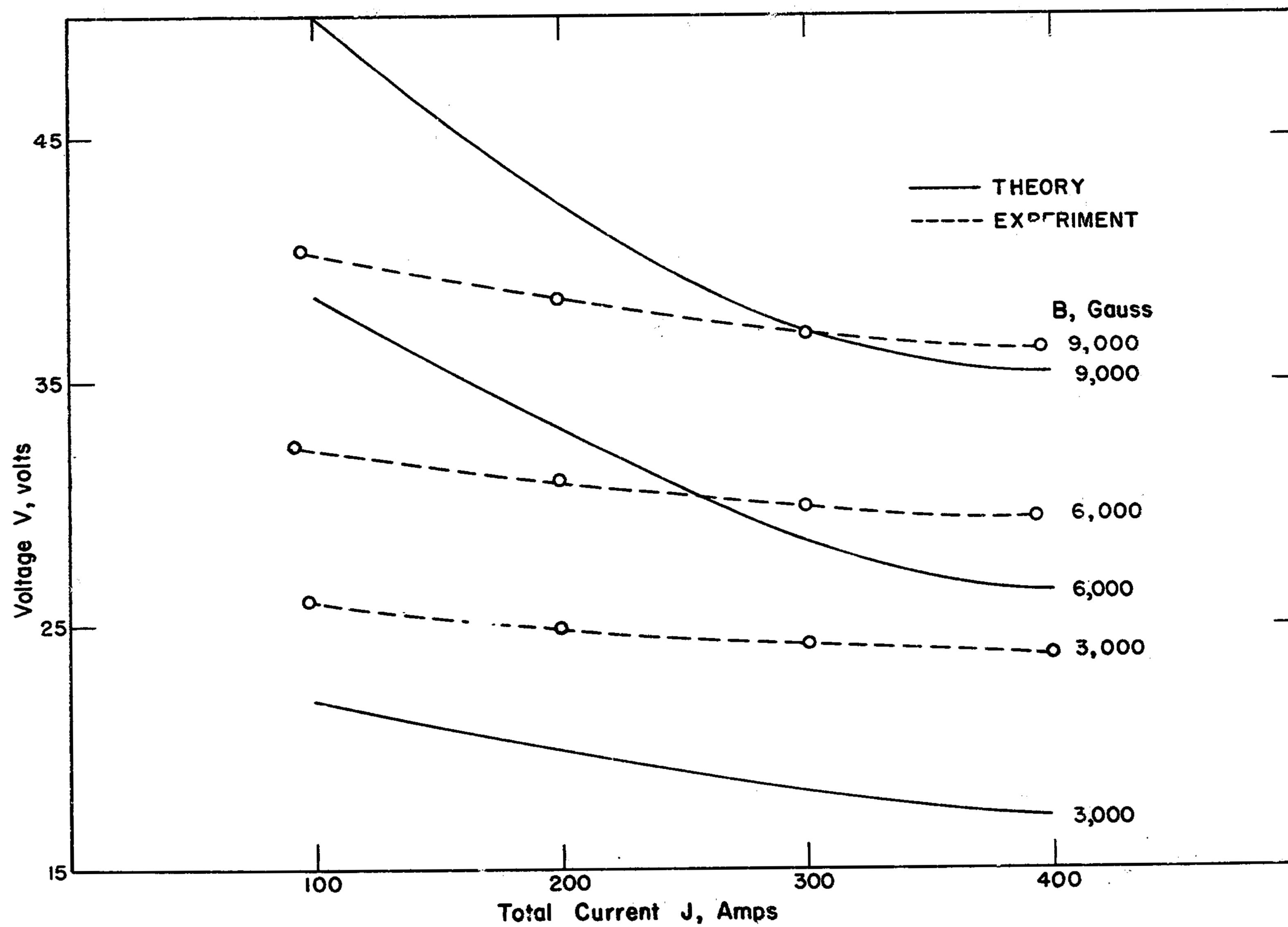
Another feature of such devices is the appearance of Hall currents. In order to obtain high degrees of ionization one has to use a monatomic gas at low pressure. As the density is decreased, Hall currents become important and cannot be ignored. These currents may be used to accelerate the flow, such as in the so-called Hall current accelerators.

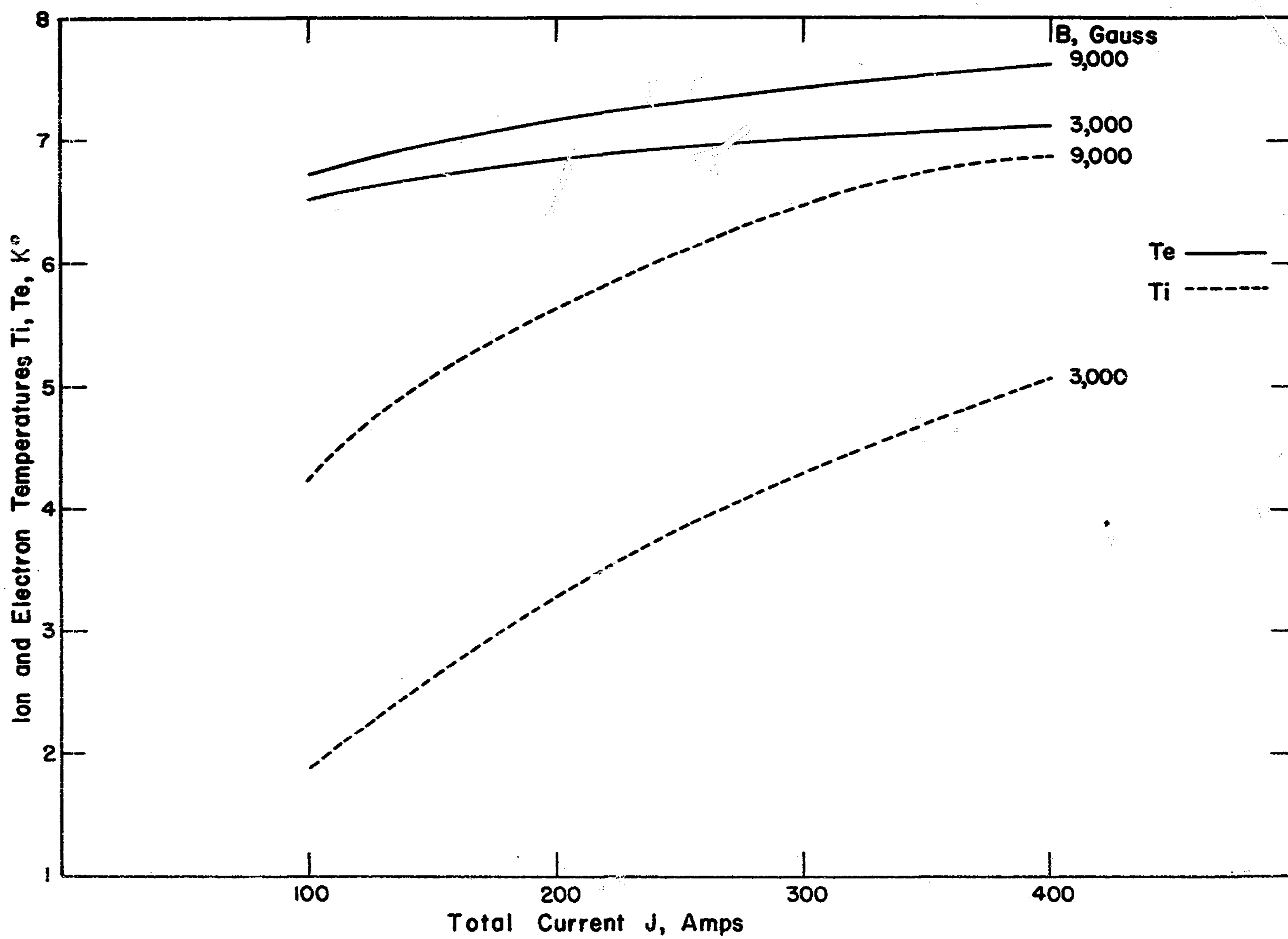
The first method developed for analyzing such devices assumes that gradients may be neglected. Such an analysis establishes the maximum theoretical performance of a given accelerator at an established set of operating conditions. Thus, for a given power input, a given magnetic field and a given chamber pressure one can predit the electron, ion and neutral temperature, the degree of ionization, the Hall current, the voltage current characteristics and the accelerating force.

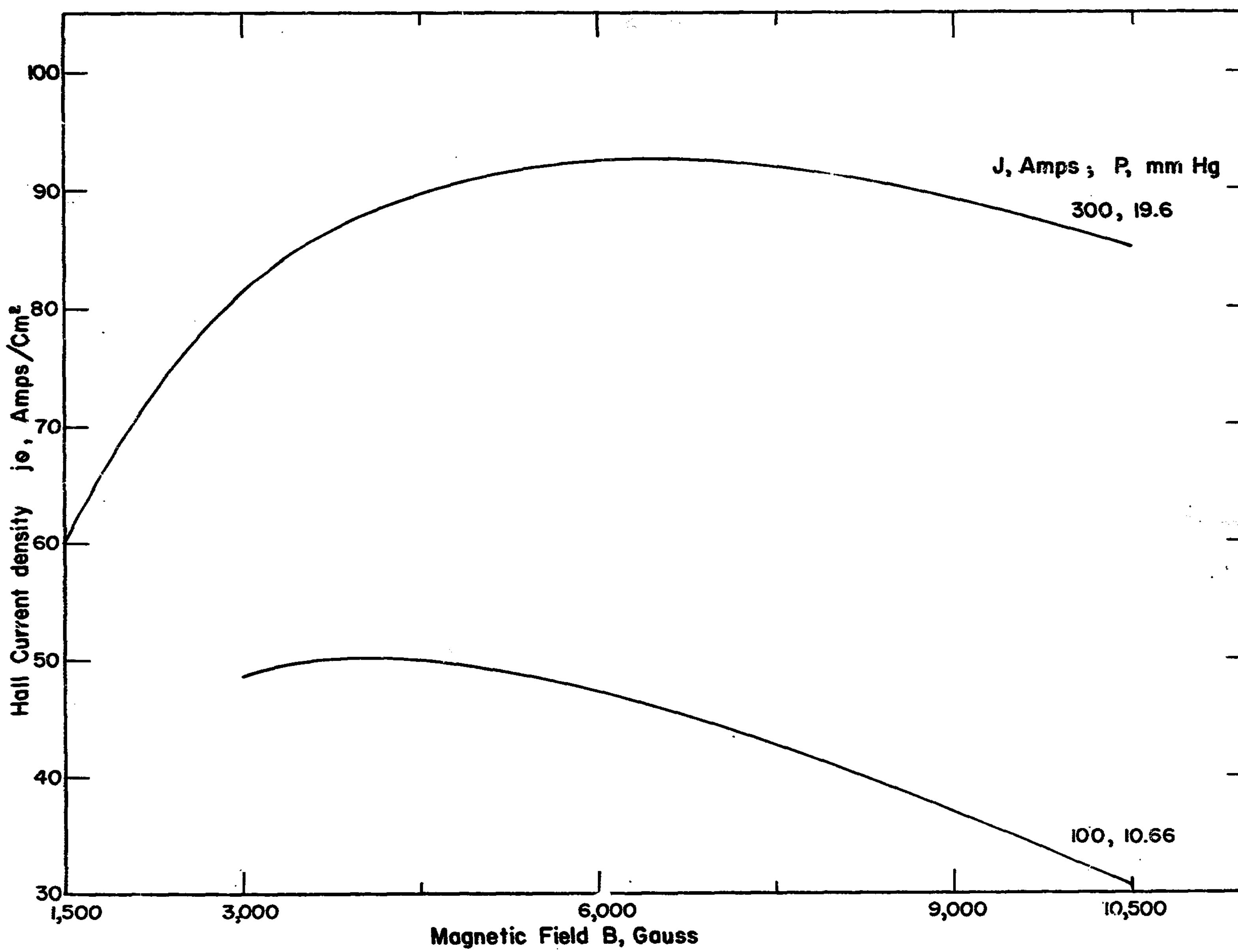
The second method being developed accounts for the presence of gradients. As a first step in employing such a method, one needs expressions for the heat flux vectors, stress tensors and diffusion velocities of the electrons, ions and neutrals. This initial stage has been completed, and the results are being used to analyze a coaxial Hall current accelerator and a linear Hall current ion accelerator.



J, Amps, P, mm Hg
100, 10.66
200, 13.4
100, 10, 66
200, 13, 4
THEORY
EXPERIMENT
60
50
40
30
20
10
Voltage V, volts
1,500
3,000
6,000
9,000
12,000
Magnetic Field B, Gauss


THEORY
EXPERIMENT
B, Gauss
9,000
9,000
6,000
6,000
3,000
3,000
45
35
25
15
Voltage V, volts
100
200
300
400
Total Current J, Amps


B, Gauss
9,000
3,000
9,000
3,000
Te
Ti
Ion and Electron Temperatures Ti, Te, K°
Total Current J, Amps
8
7
6
5
4
3
2
1
100
200
300
400

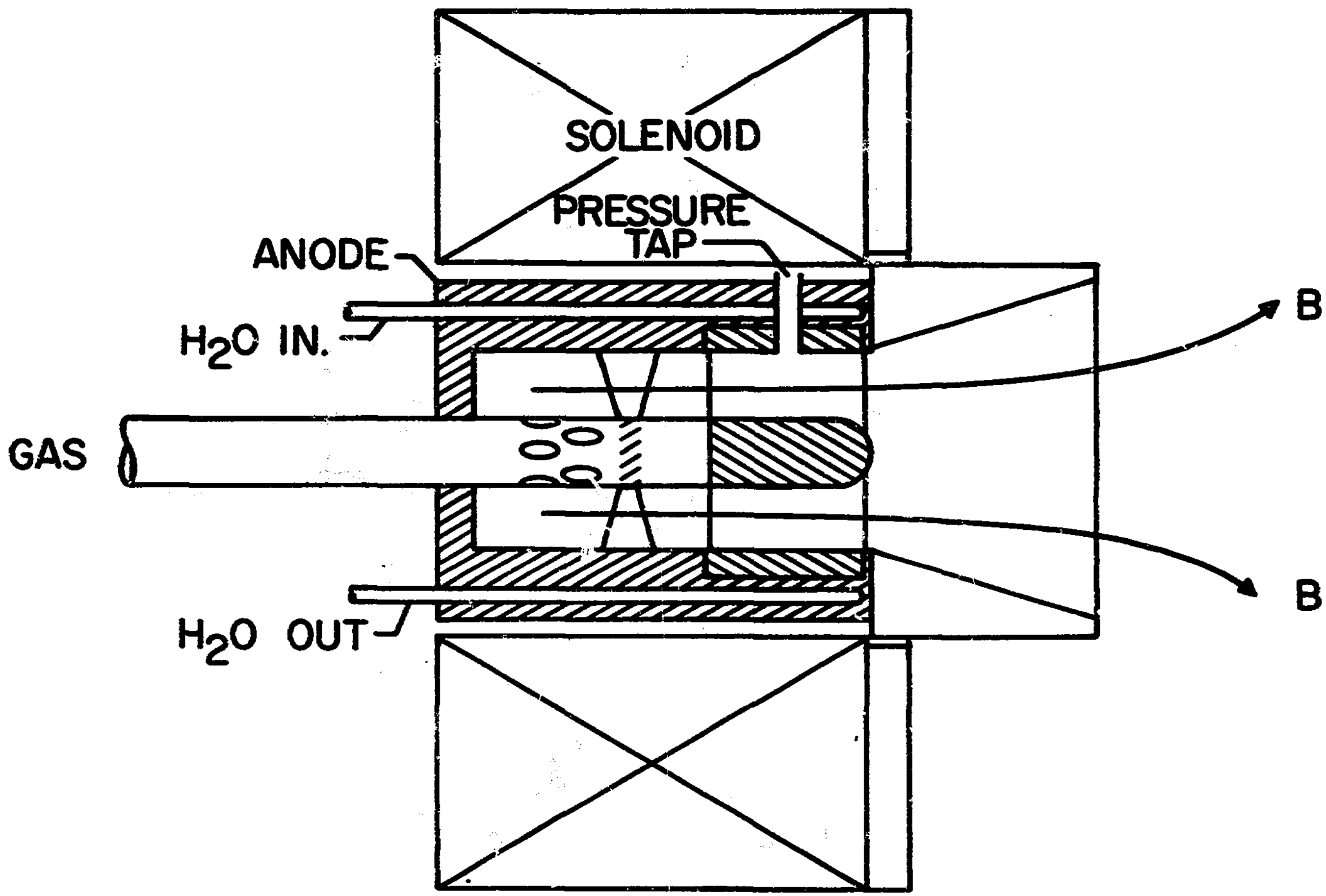

J, Amps ; P, mm Hg
300, 19.6
100, 10.66
Hall Current density jθ, Amps/Cm²
Magnetic Field B, Gauss
100
90
80
70
60
50
40
30
1,500
3,000
6,000
9,000
10,500

III, 9 NONEQUILIBRIUM IONIZATION IN STEADY DISCHARGES CROSSED WITH MAGNETIC FIELDS FOR HIGH PRESSURE MHD STUDIES. EXPERIMENTS

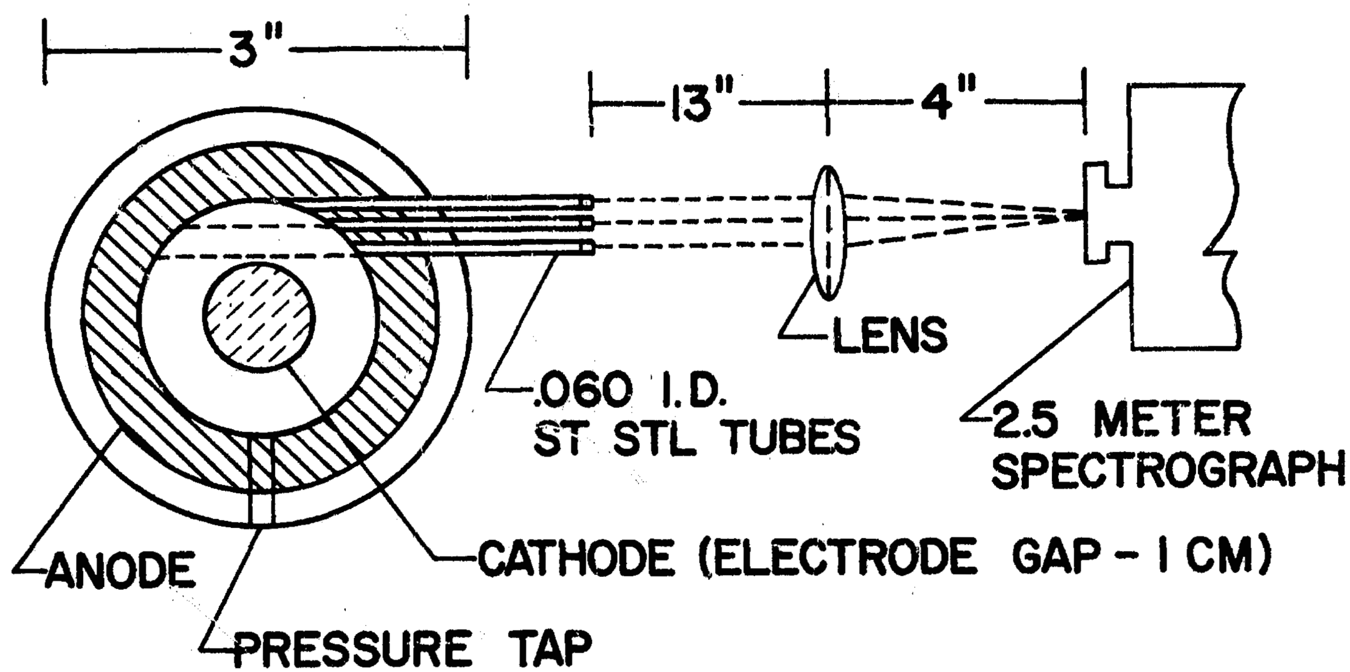
W. Grossmann, R. V. Hess, G. Oertel, F. W. Bowen
and N. W. Jalufka
NASA Langley Research Center
Hampton, Virginia

Nonequilibrium ionization has been studied for MHD generators for which it is difficult to vary the operating conditions over a wide range and to control the discharge in the rectangular channel. The present experiments concern a steady radial discharge in an axial magnetic field, which has the advantage of being diffusely distributed with cylindrical symmetry. The transition to diffuse discharge has been observed by Kerr cell photographs as well as by subsiding of fluctuations measured with electrostatic probes and with magnetic probes, which were also used in Hall current measurements. Spectroscopic measurements of the radial distribution of electron temperatures and densities are in reasonable agreement with theory for nonequilibrium ionization, with $T_e > T_i$, which will be presented in another paper. The variation of pressure in the radial direction is compared with theory for Hartmann flow. Voltage current characteristics and voltage magnetic field characteristics are also presented for currents from 100 to 500 amperes, magnetic flux densities from 3000 to 13000 gauss (and possibly 35000 gauss, if the new magnet arrives) and pressures from 10 to 50 mm.

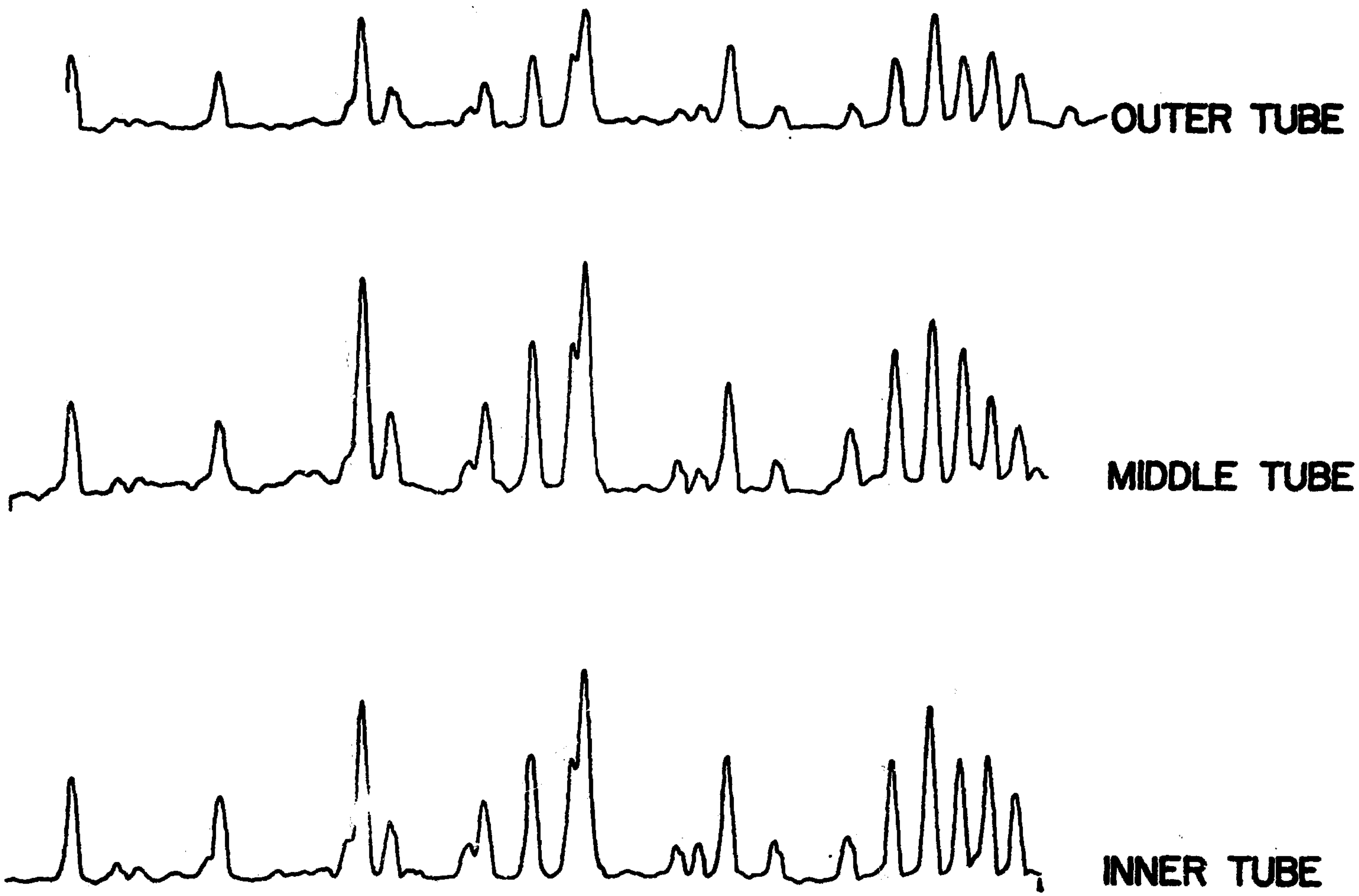
SCHEMATIC OF APPARATUS



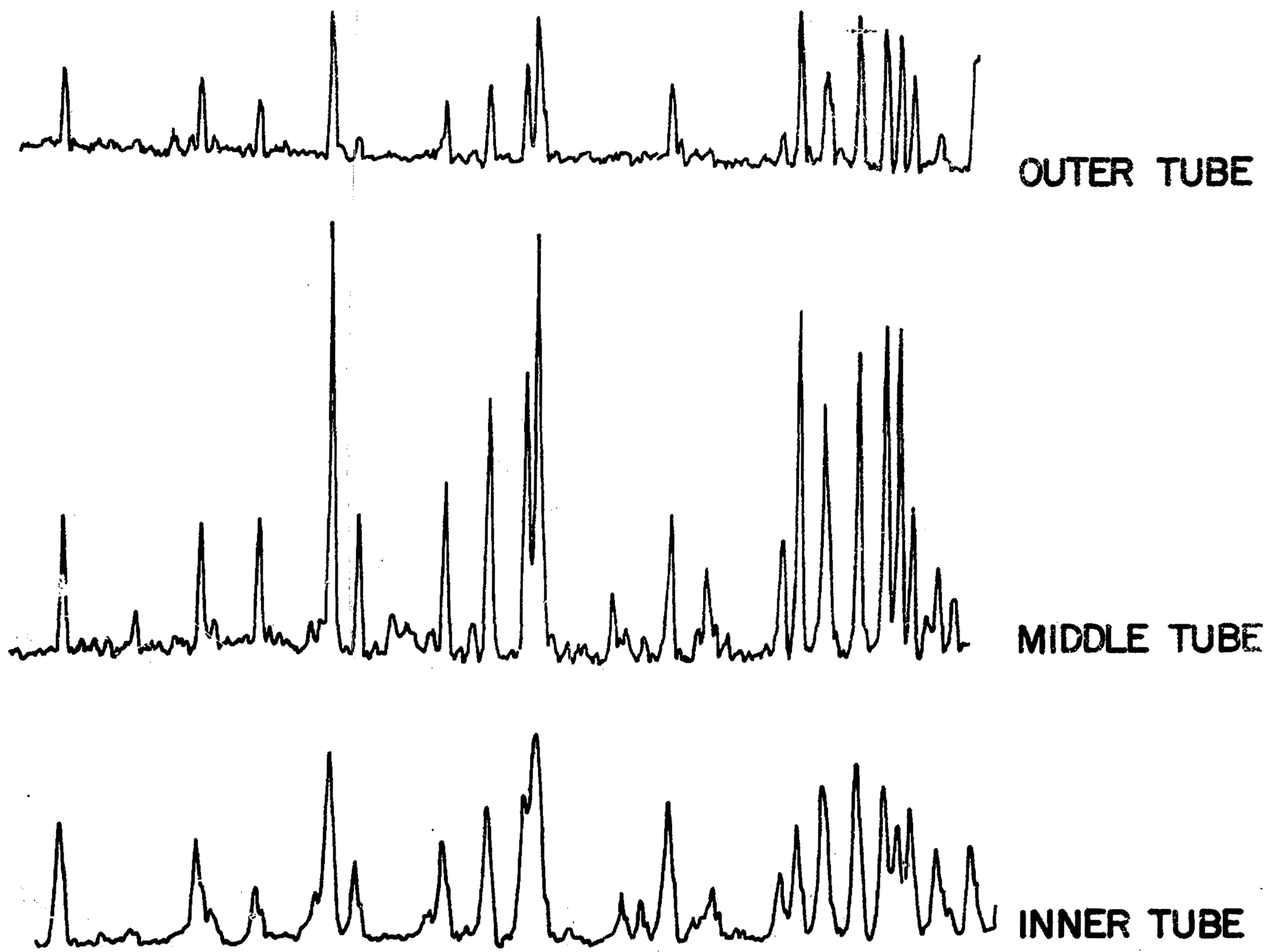
SCHEMATIC SHOWING ARRANGEMENT FOR SPECTROGRAPH MEASUREMENTS



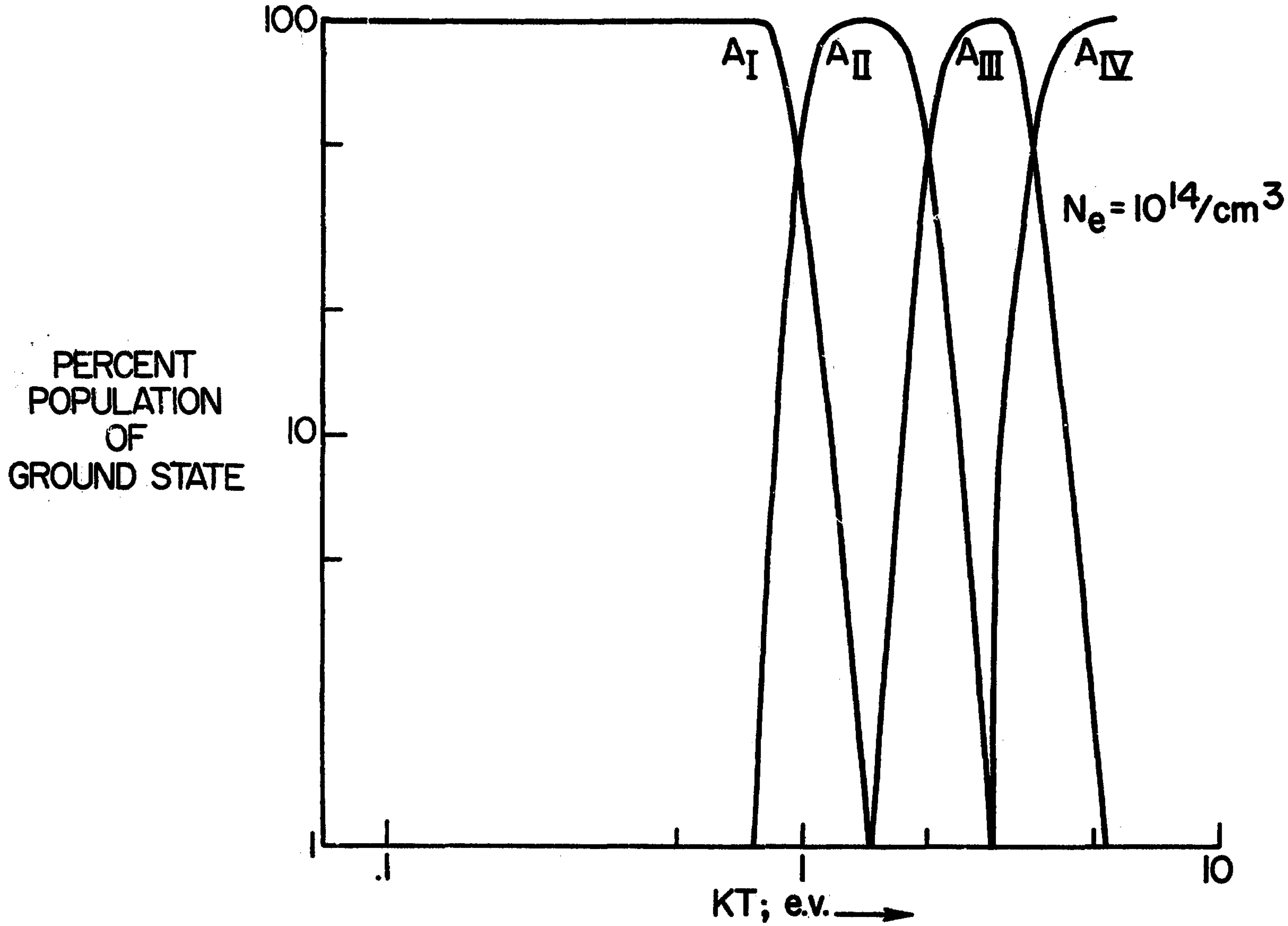
MICRODENSITOMER TRACE OF SPECTROGRAM
100 AMPS, 3,000 GAUSS



MICRODENSITOMER TRACE OF SPECTROGRAM
100 AMPS, 12,000 GAUSS



GRAPH OF PERCENT POPULATION VS KT (GROUND STATES)



III, 10 PROGRESS REPORT ON THE DESIGN AND PERFORMANCE STUDY FOR A CROSSED-FIELD PLASMA ACCELERATOR FOR A REENTRY FACILITY

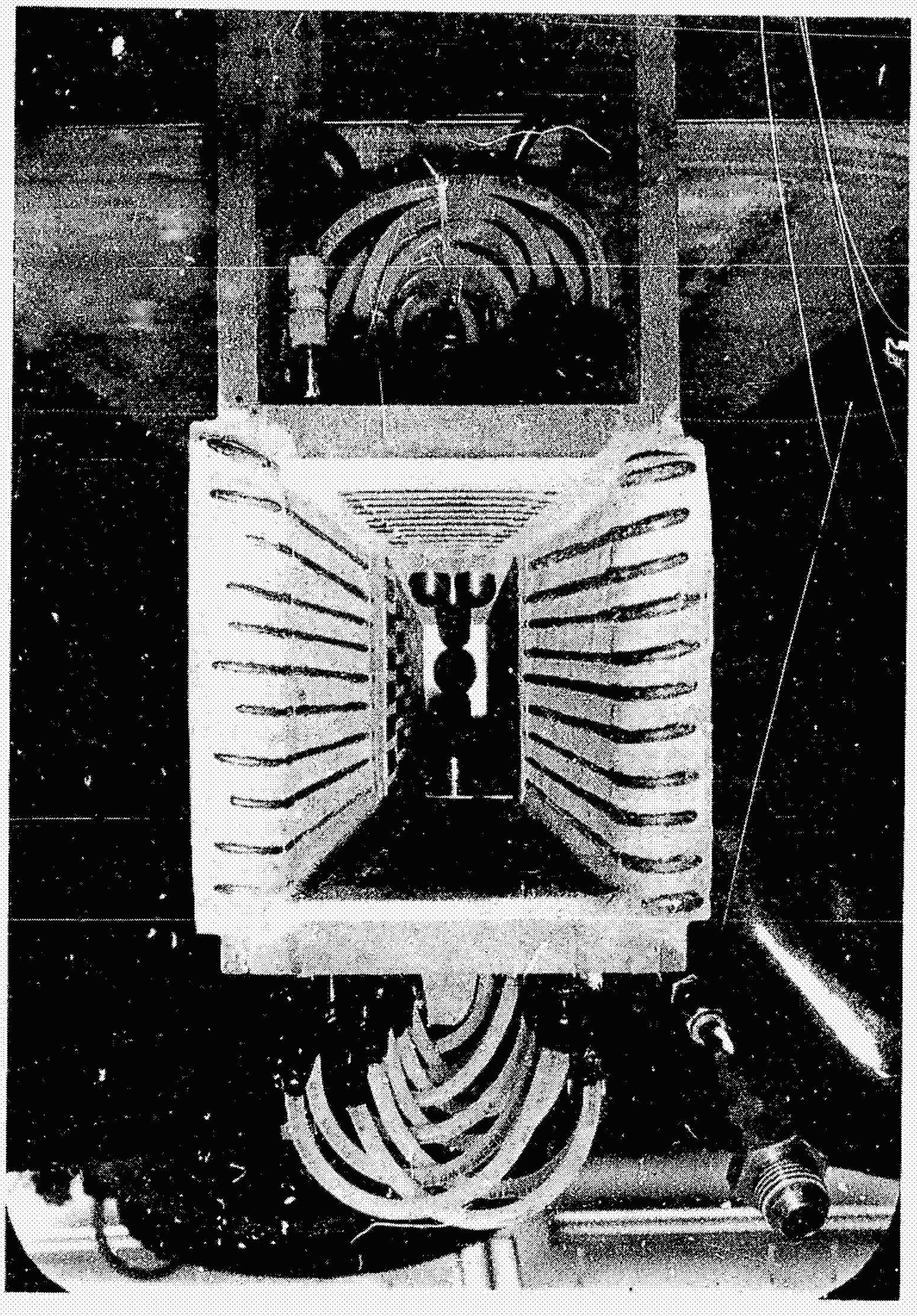
P. Lenn, G. Bedjai, D. Ward and B. Wilkinson
Northrop Company
Hawthorne, California

and

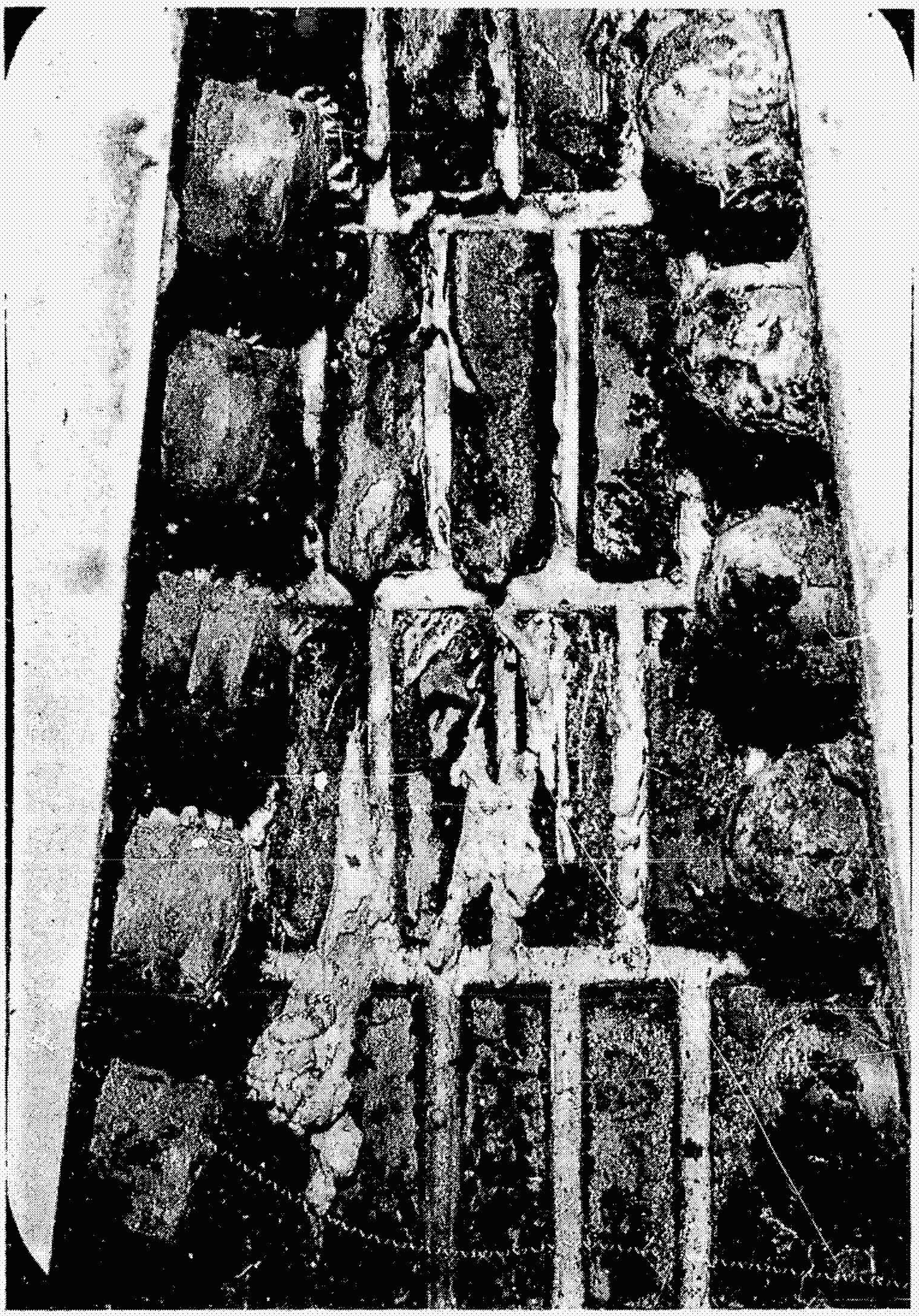
R.C. Brumfield and V.H. Blackman
MHD Research, Inc.
Newport Beach, California

NAS2-1170

The operation of a linear crossed-field accelerator operating with a supersonic flow of preheated air and designed for use as a wind tunnel source is analyzed. The criteria for selection of appropriate operating conditions are discussed. On the basis of the analysis, performance requirements, and practical considerations, an accelerator design has been developed and is discussed. The performance requirements are to accelerate an air stream having a mass flow rate of 0.01 lb/sec to a velocity of 25,000 ft/sec with a uniform velocity to within 5% over an area of 0.2 ft^2. The device should be capable of continuous operation for five minutes and should introduce into the gas stream contamination of less than 1% by weight. The practical construction of the accelerator and the experimental setup for testing are described. A discussion of the experimental tools to be used in characterizing the flow is presented. An error analysis of the experimental program is also presented.



ACCELERATOR CHANNEL



ELECTRODES AFTER TEST RUN

TABLE 2

PERFORMANCE DATA FOR TESTS 1, 2 and 3 of CA-1.

TEST CONDITIONS ARE DESCRIBED IN TABLE 1.

Test No	Electrode Pair	I_o (amp)	V_o (volts)	P_{acc} (kw)	B Webers/m^2	Φ_{acc} (Newtons)	$\frac{\Phi_{acc}}{hI_oB}$	$U_o - U_f$ (m/sec)	η_{acc} %	Tank Pressure mm/Hg	Duration of acc. Test (sec.)
1	1	200	190	38	0.05					7.0	165
	2	200	150	30	0.05	o(0.5)*	o(0.2)	(100)	o(0.1)		
	3	200	120	24	0.05						
	4	200	100	20	0.05						
	5	200	100	20	0.05						
	(Total)	1000		132							
2	1	200	280	56	0.10	3.78	1.03	833	2.49	0.7	181
	2	200	210	42	0.10						
	3	200	185	37	0.10						
	4	200	170	34	0.10						
	(Total)	800		199							
3	1	300	300	90	0.10	4.17	0.65	918	2.23	1.3	92
	2	300	220	66	0.10						
	3	300	170	51	0.10						
	4	230	155	35	0.10						
	5	100	150	15	0.10						
	(Total)	1230		257							

* o(x) = of the order of

III, 11

RESEARCH ON LINEAR CROSSED-FIELD STEADY-FLOW ACCELERATORS

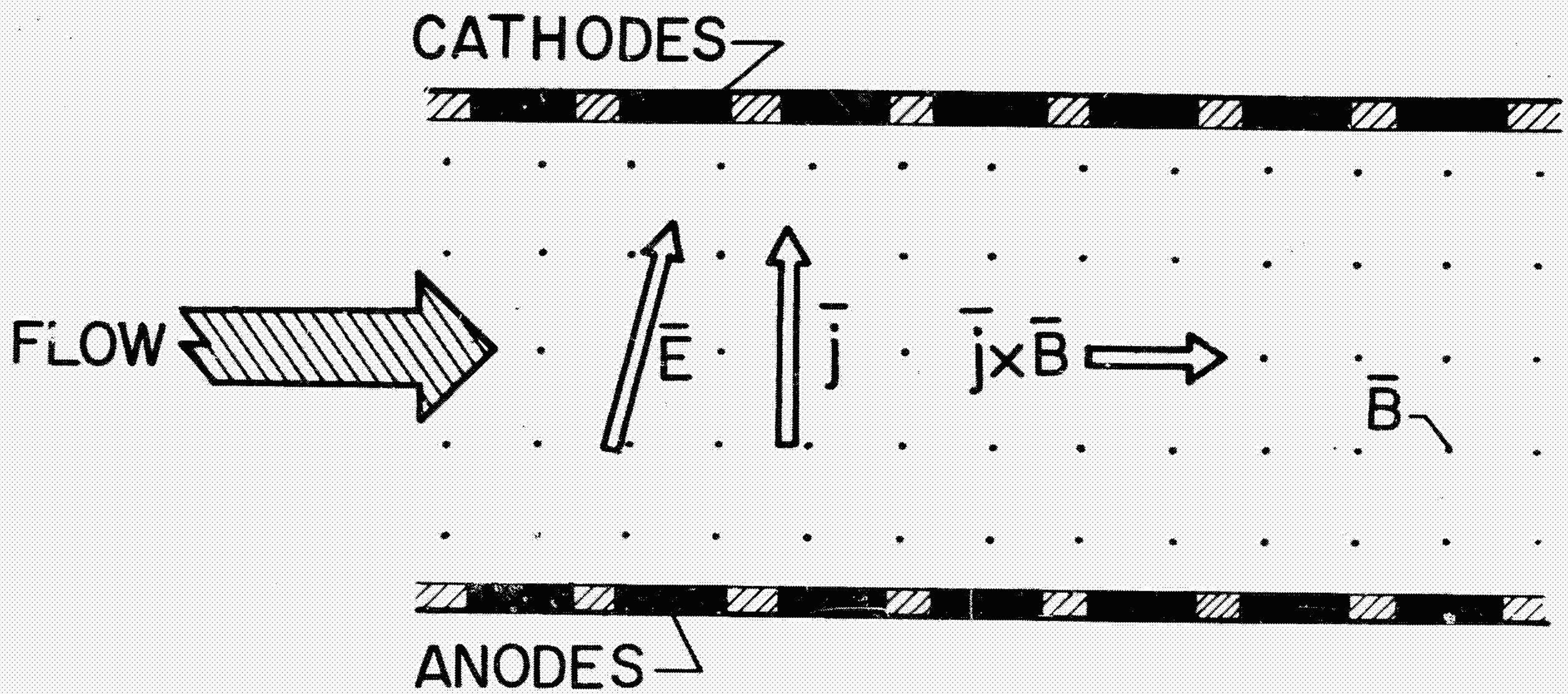
F. Carter, A. P. Sabol, D. R. McFarland,
W. Weaver and G. P. Wood
NASA Langley Research Center
Hampton, Virginia

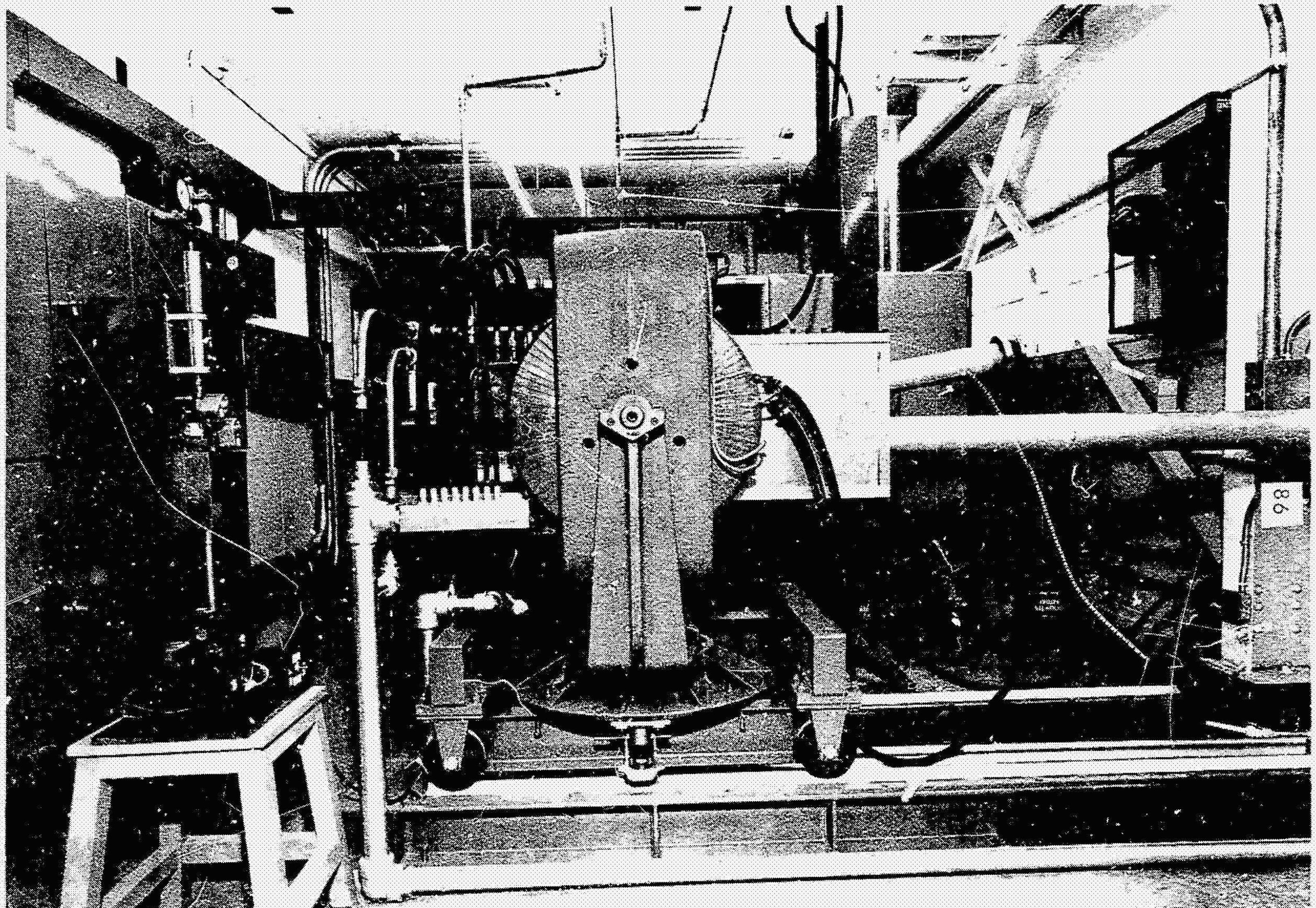
Since the last meeting, research on a 1 cm. square steady-flow plasma accelerator has been continued. The enthalpy of the arc heater that supplies the plasma for the accelerator has been doubled. The need for seeding of the nitrogen with cesium has been eliminated. Water cooling of cathodes and anodes has been introduced. The channel has been changed from constant area of 1 cm. square to an expanding channel 1 cm. square at one end and 1 cm x 4 cm at the other. The length is 8-3/4 cm. There are 7 pairs of electrodes 1 x 3/4 cm. The magnetic field is 5300 gauss and the static pressure in the accelerator is of order 40 mm Hg. A new power supply of higher voltage has been put into use. Approximately 75 amperes of current are put through the plasma by each pair of electrodes.

Since the last meeting research has begun on a new and larger accelerator. This one is 1 x 1 x 12 inches. Much work has been done on the arc heater that supplies the plasma for the accelerator. The arc position has been stabilized by means of a reverse curve in the magnetic field that rotates the discharge. Seeding through the central electrode (rather than into a settling chamber) has been accomplished for the first time by employing several "tricks". (The power supply for this accelerator does not have sufficient voltage for seeding to be eliminated.) Improvements in the operation of the accelerator are being continually made.

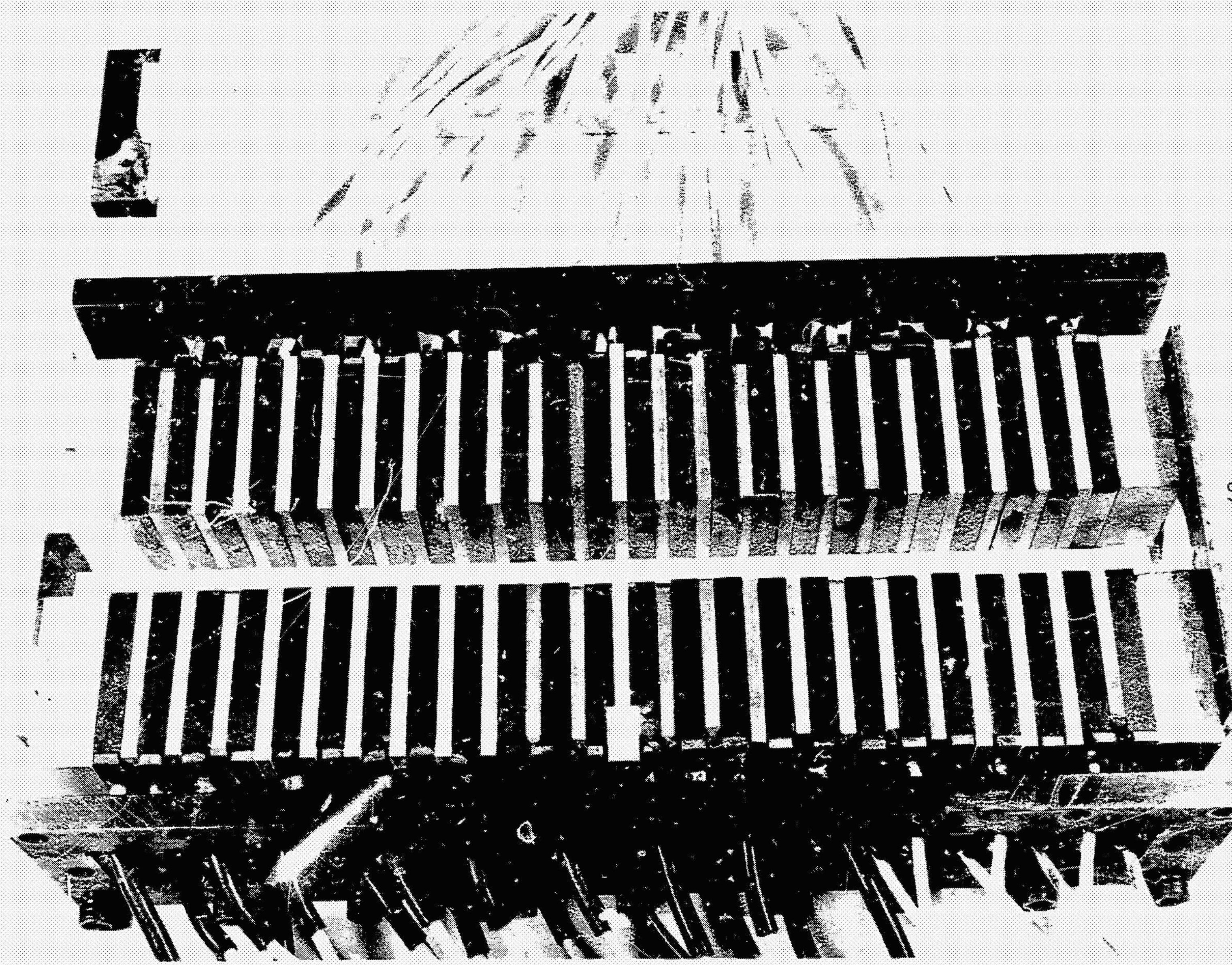
A new and larger accelerator is being designed. It will be 2 x 2 inches at entrance and will expand to 5 x 5 inches at exit and will have a length of 18 inches. Ten megawatts will be used to operate the arc heater and another 10 to operate the accelerator. The gas will enter the accelerator at 6000 ft per sec and is expected to leave at about 40,000 ft/sec with a density corresponding to an altitude of about 175,000 feet.

SCHEMATIC OF CROSSED-FIELD ACCELERATOR





1 x 1 x 12" ACCELERATOR INSTALLATION



CUT-AWAY OF 1 x 1 x 12" ACCELERATOR CHANNEL

III, 12

REDUCTION OF ELECTRODE EROSION IN CONTINUOUS PLASMA ACCELERATORS THROUGH USE OF EXTERNALLY R-F HEATED RING CATHODES

R. H. Weinstein, R. V. Hess, O. Jarrett and D. R. Brooks
NASA Langley Research Center
Hampton, Virginia

One of the most important problems in the operation of continuous plasma accelerators is the reduction of electrode erosion. In view of its azimuthal symmetry, the Hall current accelerator offers the possibility of uniform current distribution over the electrode surfaces; also, for the linear Hall accelerator where the electrodes are at the ends of the accelerating region a measure of independent control of electrode phenomena is possible. Experiments have been performed with an externally r-f heated ring cathode operating with a linear Hall accelerator. The cathode is uniformly heated to thermionic temperatures and the discharge is also uniform. Some capacitive coupling into the gas flow has been shown to be useful in starting and maintaining the discharge. This effect is being exploited in a separate device with the aim to provide both thermionic, as well as ionization, control near the cathode.

III, 13

MAGNETIC EXPANSION PLASMA THRUSTOR

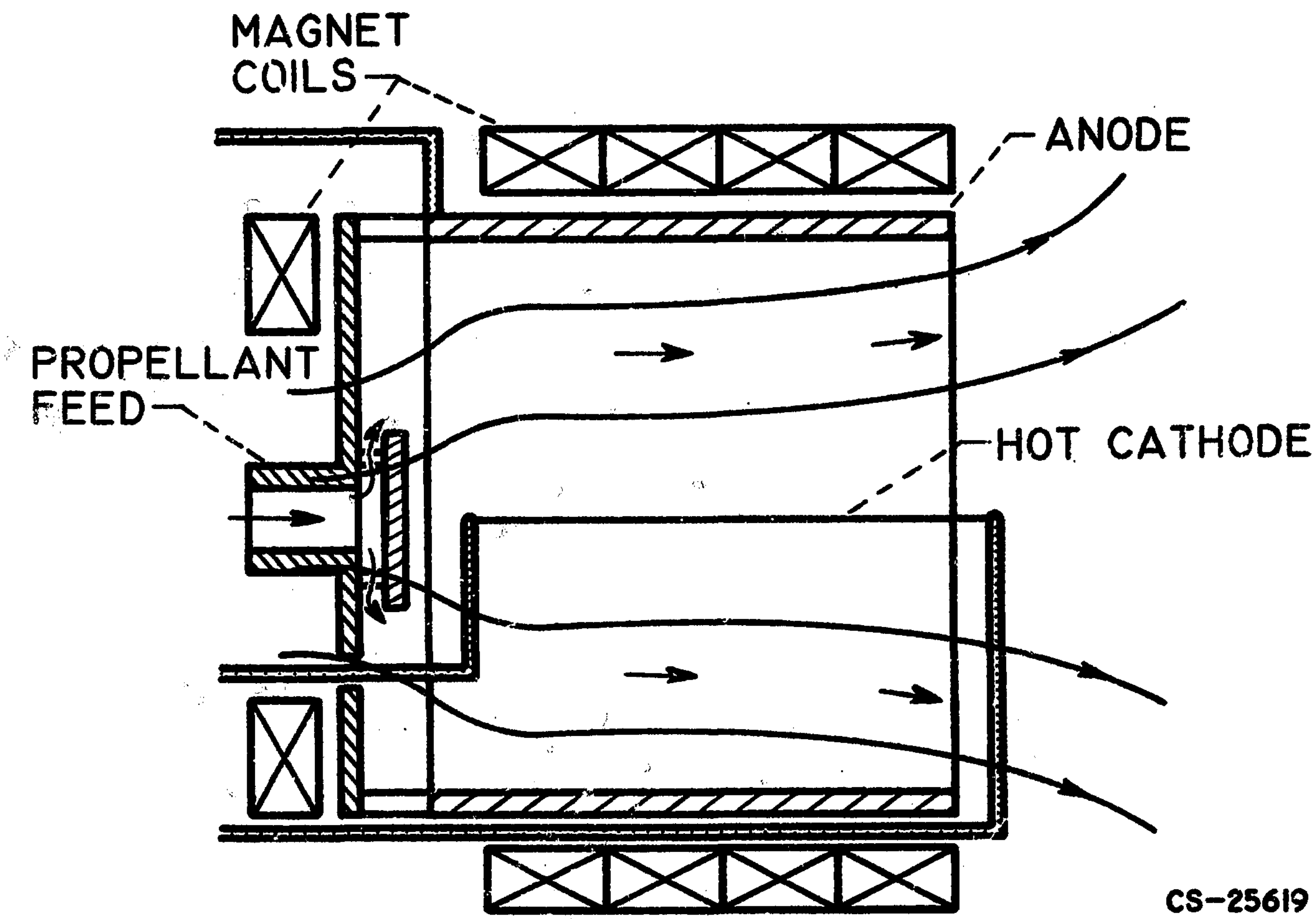
(Part 1)

G. R. Seikel
NASA Lewis Research Center
Cleveland, Ohio

In low density plasma heating the electric power is added directly to the random energy of the plasma's electrons. The resulting high energy electrons ionize the propellant, and, if the plasma is exhausted from the discharge chamber into a vacuum, the random electron energy is converted to directed energy in the expansion process. If the device is electrically isolated, there can be no net current flow, and the expanding electrons must drag the ions along. Physically, this is accomplished by an electric field set up by the plasma itself. This field retards the expansion of the electron gas and accelerates the ions. The energy added to the ions is at the expense of the random electron energy. The expansion process can be controlled by the magnetic nozzle action of a spatially varying axial magnetic field. The power can be added to the plasma's electrons by d-c, a-c, or r-f. One interesting characteristic of such thrustors is that they can operate at low power levels, and thus may be attractive for low thrust missions such as station keeping and attitude control of a satellite in a 24-hour orbit.

Results of some pertinent d-c and r-f discharge experiments at Lewis have been previously presented. Domitz' d-c experiments (ref. 1) show the physical existence of the ion accelerating electric field and can be used to demonstrate that the energy to accelerate the ions must be at the expense of the random electron energy. In addition some unpublished results indicated the dependence of the expansion process on the magnetic nozzle. Sovie and Seikel's r-f experiments at 17.5 mc (ref. 2) show that low density energetic electron plasmas can also be produced in modest magnetic bottles with r-f induction heating. Coupling efficiencies above 70% have been obtained. The equivalent efficiency in a low voltage (0-50 volt) hot cathode d-c discharge may be less than 70% based upon Kaufman's estimate of a 10-30 electron volt per electron emitted minimum for cathode heater power (ref. 3). In higher voltage hot cathode discharges the cathode erosion problem seems insurmountable. In general the operating life of the r-f discharge appears to be superior, but power conditioning is more difficult. However, power transistors are presently available for at least up to 50-150 watts at 25 mc.

A mission study is being made to determine the desirable characteristics of an electric thrustor for solar battery powered attitude control and orbit correction missions. Results of this study indicate that thrustor efficiency may not be the dominant factor. Typically for a 500 lb. satellite in a stationary orbit for two years, the total weight of the power supply and propellant for a thrustor of only 10% efficiency may well be less than the weight of the thrustors themselves. Thus, the most stringent thrustor requirements appear to be their reliability and weight. The desired thrust level for such a mission is on the order of 0.5×10^{-3} newtons (10^{-4} lbs). The optimum specific impulse is in the range of 1000 to 5000 seconds depending on the system efficiency. An additional result of this study is that for such missions the crossover time for the propellant plus power plant weight of an ideal electric system to be less than the propellant weight of even a 450 second chemical system is only approximately one month.



MAGNETIC EXPANSION PLASMA THRUSTOR

III, 14

MAGNETIC EXPANSION PLASMA THRUSTOR

(Part 2)

S. Domitz
NASA Lewis Research Center
Cleveland, Ohio

Additional experiments have been conducted with the d-c device of reference 1 to directly measure thrust efficiency and specific impulse using the source as a d-c thrustor. The thrustor consists of a hot filament, coaxial, discharge in a magnetic nozzle. Measurements are made with a pendulum thrust stand in a low pressure environment. Experimental techniques utilized to determine these low thrusts will be discussed. For a given mass flow both the efficiency and the specific impulse increase with applied voltage. For a constant voltage there is an optimum current for maximum efficiency. The magnetic field strength must be optimized for each setting of power and mass flow. Typical thrust levels with argon propellant are between 1×10^{-3} to 5×10^{-3} newtons at flow rates of the order of .2 mg/sec, and power inputs of a few hundred watts. Data has been taken up to specific impulses of 2000 seconds. Typical thrust efficiency based upon the power to the plasma is 10% at 1500 seconds.

References:

1. Domitz, Stanley: Experimental Evaluation of a Direct-Current Low-Pressure Plasma Source. NASA TN D-1659, 1963.

2. Sovie, R. J., and Seikel, G. R.: rf Induction Heating and Production of Plasmas. Bull. Am. Phys. Soc., Vol. 8, no. 2, 1963.

3. Kaufman, H. R.: The Electron-Bombardment Ion Rocket. Third Symposium on Advanced Propulsion Concepts, Cincinnati, Ohio, October 2-4, 1962.

IV, 1

TRAVELLING WAVE ACCELERATOR

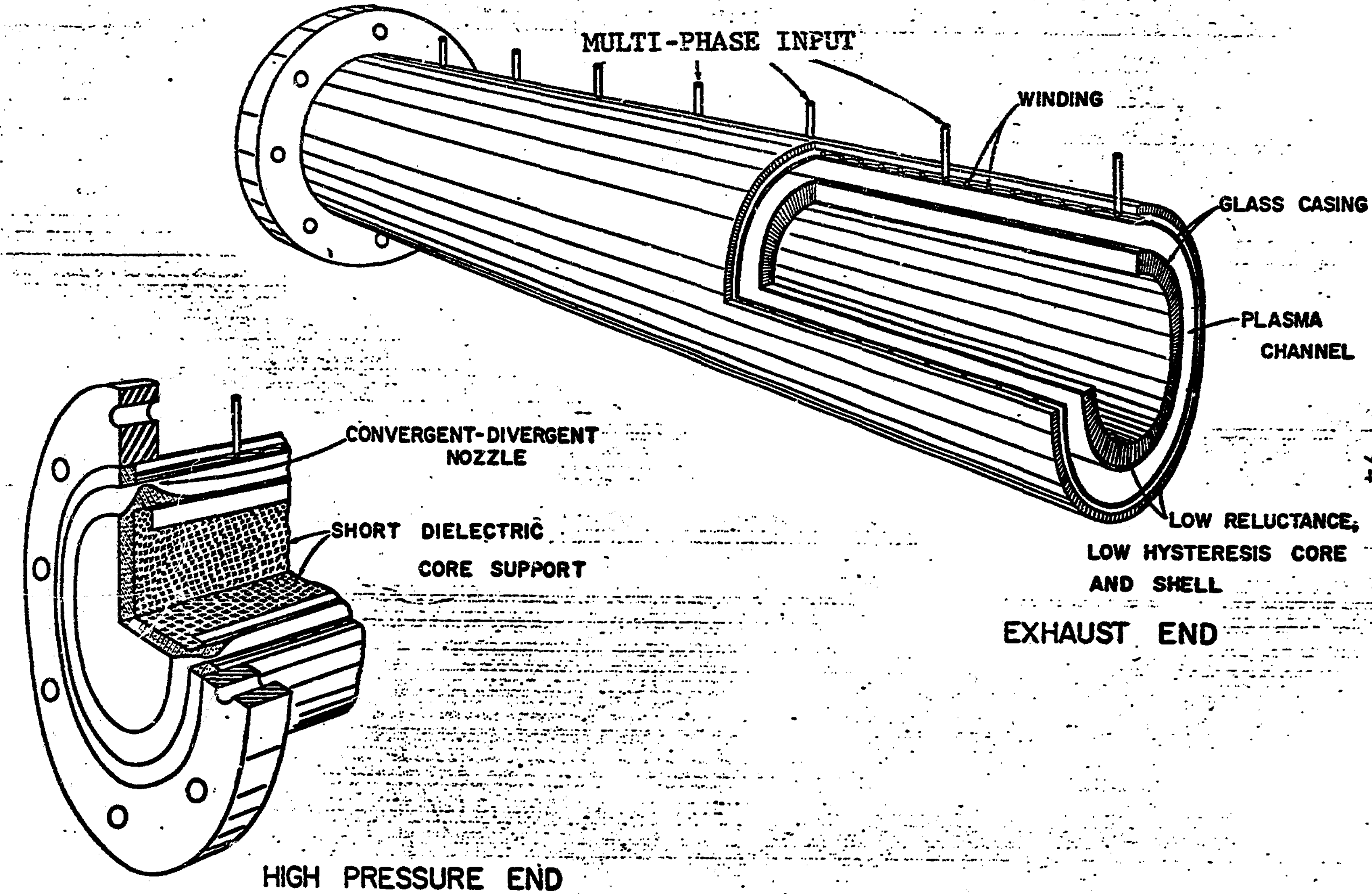
M. Lessen
The University of Rochester
Rochester, New York
NsG-350-63

The purpose of this study is to investigate the feasibility of a travelling wave device of rotationally symmetric geometry for propulsion. Both an analytical and experimental approach are being pursued. The concept is to accelerate a cold plasma from a low inlet velocity to exit velocities in the range of fifteen to twenty thousand meters per second. The high frequency magnetic field transfers energy to the ionized particles which are rapidly accelerated and experience charge exchange collisions with neutral atoms present in the medium. This type of encounter between fast ions and slow neutrals produces a fast neutral and slow ion which is subsequently influenced by the magnetic field and the process is repeated.

While there are three different species present, ions, slow neutrals and fast neutrals we first considered a model representing the average properties of the plasma, and are now concerned with the multi-component fluid model. An additional boundary value problem concerned with the field geometry has been approached. Solutions to a simplified model have been effected.

Experimentally, the project has involved: the design and construction of penetrations into the vacuum pumping facility into which the device will operate; design and construction of a travelling wave tube and winding, selection of an economical core material for the external magnetic circuits and construction of same and finding and securing a satisfactory multiphase a.c. machine for the device. (This basic tube design is illustrated in the figure.) We have also been involved in the design and construction of a glow discharge chamber and appropriate power supply to be used as a possible cold plasma source and the design of probes for diagnostic purposes with regard to a.c. magnetic flux.

The above experimental work has occupied considerable time but is well on its way to completion and is certainly necessary to verify the several assumptions used in the analysis, for example, the importance of charge exchange phenomena.



TRAVELLING WAVE CHANNEL
DEPT. of MECHANICAL ENGINEERING
THE UNIVERSITY of ROCHESTER
Rochester, New York

IV, 2

THE TRAVELING MAGNETIC WAVE PLASMA ENGINE

R. E. Jones and R. W. Palmer
NASA Lewis Research Center
Cleveland, Ohio

The previously reported experimental traveling magnetic wave plasma engine at Lewis Research Center (ref. 1) has been modified to reduce the high heat transfer losses to the tube walls downstream of the last coil. This high heat transfer rate arises because the magnetic field lines diverge after the last coil and direct the plasma to the wall. The present configuration uses a three-inch diameter pyrex tube which is flared out to six inches diameter immediately downstream of the last coil. This geometry has been tested using four coils with four phases and ten coils with four phases. Both Argon and Xenon gas have been used as the propellants. These coil systems were driven by two 13 kilowatt power supplies at a frequency of 150 kilocycles. The coils were spaced to correspond to the optimum ratio of coil radius to magnetic wave wave-length determined in the theoretical study of reference 2. The magnetic wave speed for both the four-coil and the ten-coil engines corresponds to a specific impulse of 4650 seconds. For the four-coil engine the efficiency determined by thrust measurements was 9 percent at a specific impulse of 3200 seconds with Argon gas and increased to 26 percent at an impulse of 4000 seconds when Xenon gas was used. Increases in performance are expected with increasing molecular weight of the propellant due to a reduction in the diffusion rate of the heavier molecules to the tube wall. There was, however, no substantial difference in the performance of the ten-coil engine over that of the four-coil engine. The accompanying figure compares data of the four-coil engine with that of the previously reported four-coil engine installed on an unflared tube. All efficiency calculations are based on power actually transferred to the gas.

References:

1. Jones, R. E., and Palmer, R. W.: Traveling Wave Plasma Engine Program at NASA Lewis Research Center. Third Symposium on Engineering Aspects of Magnetohydrodynamics, Univ. of Rochester, March 1962.

2. Palmer, R. W., Jones, R. E., and Seikel, G. R.: Analytical Investigations of the Coil System Design Parameters for a Constant Velocity Traveling Magnetic Wave Plasma Engine. Proposed NASA Technical Note.

PRECEDING PAGE BLANK NOT FILMED

IV, 3

TRAVELLING-WAVE ACCELERATOR

W. H. Braun
NASA Lewis Research Center
Cleveland, Ohio

The travelling-wave accelerator is represented by a simple, two-dimensional model consisting of a channel of uniform width and infinite extent. A super-imposed sinusodial wave of magnetic induction moves along the channel at speed v_w. The lines of magnetic induction are normal to the channel axis and, assuming the channel is narrow compared to a wavelength, the field may be considered uniform across the channel. The propellant enters the channel from $x = -\infty$ at a uniform density and velocity, and is acted upon by the magnetic field in the region $x \geq 0$, either because it has been shielded from the magnetic field previously or because it has become suddenly electrically conducting. In order to make the mathematical problem tractable, two assumptions are made about the propellant. First, it is assumed to remain at a constant temperature throughout, of such magnitude that the sound speed is much less than the magnetic-wave speed. This is reasonable for desired specific impulses and practical temperatures, and its consequence is that a fluid element is unaware of its neighbor's accelerations so that all fluid particles act nearly independently. At the same time it is necessary that the electron thermal speed remain appreciable in order that the concept of conductivity remain valid. A second assumption made about the fluid is that its conductivity is proportional to its density, which is justified only by the simplification it yields in the equation of motion.

The first assumption is used to make a perturbation analysis of the Lagrangian form of the equation of motion for the fluid. The second assumption provides that the system of equations so derived shall be ordinary rather than partial. It is then possible to follow individual fluid particles in their accelerated motion down the channel. Considering Joule heat as the only energy loss, it is found that the efficiency at any point in the motion is the average of the velocity at that point and the initial velocity, both normalized to the wave speed. Since the initial velocity is very small, a measure of the efficiency (and also thrust) is the average over a cycle of the exit velocity. As the fluid approaches the wave speed at large x, the perturbation process breaks down.

Numerical solutions to the zero-order equation have been obtained for three values of the interaction parameter $\sigma B_0^2/\rho_0\omega$ (ratio of ponderomotive force to inertia force). They show that the fluid tends to gather in regions of high density separated by regions in which the fluid is very rare. Every particle that enters the accelerating region at a node of the magnetic wave serves as the center for one of the high density regions. The current density is also great in these regions and drops off in the low-density regions. As the fluid moves down the channel the peaking of mass and current density becomes more severe. Assuming that a typical accelerator will be one wavelength long in order to establish the wave pattern, it is found that an interaction parameter of 1 is too large, i.e. it employs a larger magnetic field or conductivity than is needed to accelerate the fluid in one wavelength. On the other hand, an interaction parameter of 0.1 is too small. A value of about 0.3 seems to be optimum.

The assumption that the conductivity is proportional to the density has been tested assuming joule heat ionizes the fluid. It is not quantitatively correct for any particle of fluid, and qualitatively correct only for some of the particles in the high-density regions.

IV, 4

INDUCTIVE AND CAPACITIVE HEATING OF A HYDROGEN PLASMA BY A R.F. COIL

C. C. Swett
NASA Lewis Research Center
Cleveland Ohio

Experimental results for heating a plasma by a r.f. coil in the presence of an axial magnetic field are analyzed using an electric circuit model based on the geometric character of the apparatus. This model indicates that the presence of plasma adds a "lossy" capacitor in parallel with the r.f. coil Consequently power goes into the plasma both inductively (E_θ) and electrostatically (E_r,E_z). It is believed that the latter mode of power transfer is responsible for anomalies noted. The amount of power in each mode was calculated and shown to vary with magnetic field. The inductive power transfer increased at magnetic-field values near the atomic and molecular ion cyclotron fields, whereas the electrostatic power decreased or increased depending upon which parameter -- power or coil voltage -- was held constant. Maximum total power transfer also occurred near the atomic and molecular ion cyclotron fields. The electron-density decrease noted near the resonant points appeared to be related to the induction mode only. Some deficiencies of this over-simplified model are noted.

IV, 5

CONTINUOUS MICROWAVE MAGNETIC ACCELERATOR

D. B. Miller
General Electric Company
King of Prussia, Pennsylvania
NAS 3-3567

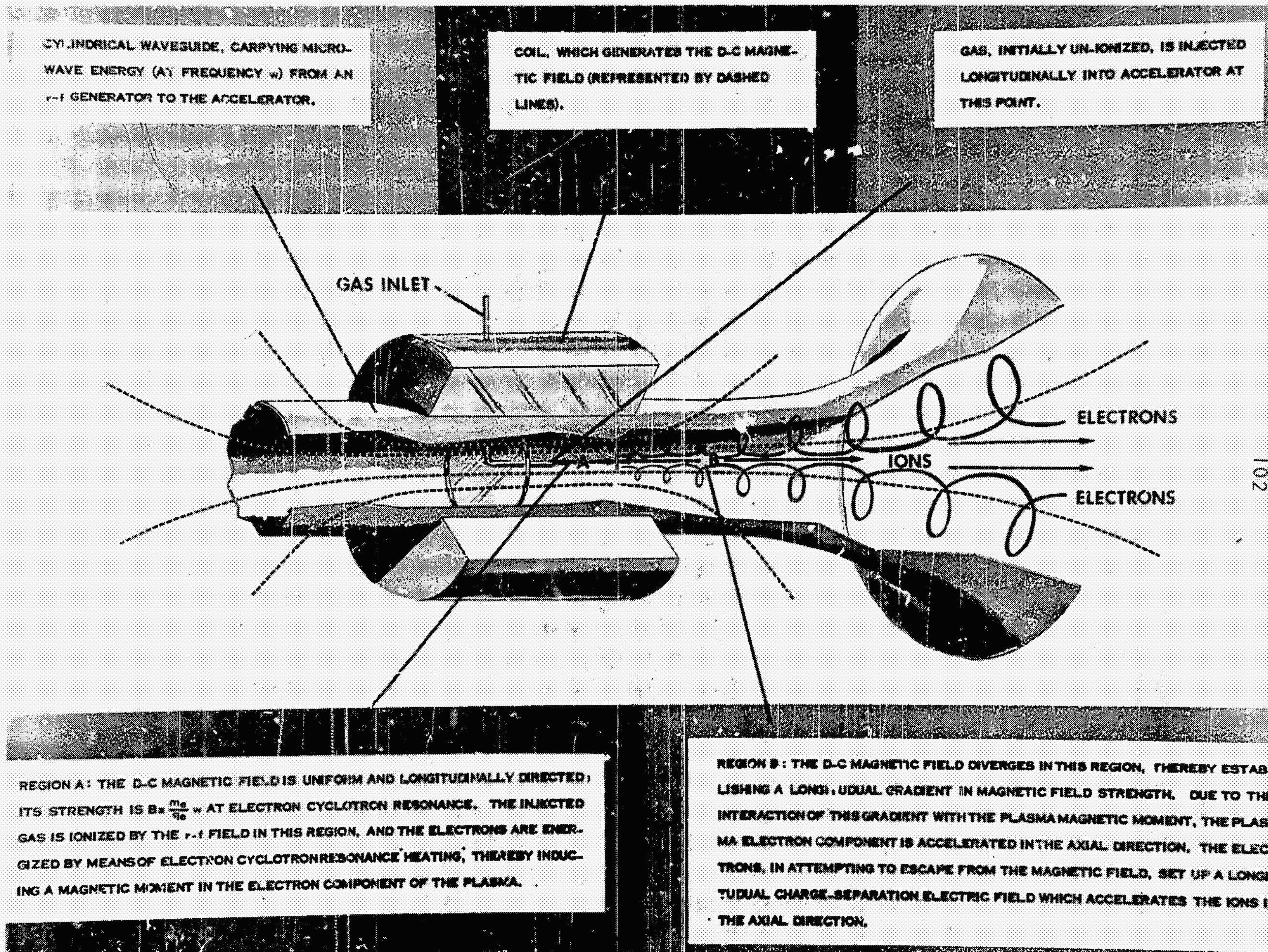
The microwave plasma accelerator being investigated is a system in which a magnetic moment is continuously induced in a flowing plasma. This occurs in the presence of a non-uniform d-c magnetic field whose direction and gradient are parallel with the magnetic moment vector. Due to the resulting Lorentz interactions, the plasma is accelerated down the field gradient. Note that the operation is both continuous and electrodeless. The magnetic moment is generated within the plasma by transferral of power from an electromagnetic field. This coupling is maximized by resonating the e-m field frequency at the electron-cyclotron-resonance frequency determined by the d-c field strength. The accompanying drawing may help clarify these processes.

One principal effort to date on this project has been to achieve a theoretical understanding of the r-f/plasma coupling. Conditions leading to a low reflection coefficient and processes by which the power is transferred from the e-m field to the plasma have been studied.

Another goal of our earlier work was to operate an accelerator in the laboratory. In the resulting experiment, a c-w, 2.45 kmc/sec, 320 watt, TE_{10} mode wave was impinged on an evacuated region of waveguide into which gas was continuously flowing. A solenoid around the guide provided the necessary resonance and diverging magnetic fields. Microwave reflection and emerging plasma power and momentum measurements were made for various gas densities and magnetic field strengths. A very low reflection coefficient (0.15) was obtainable, and as much as 22% of the power carried by the incident r-f field appeared as longitudinal motion of the accelerated plasma. Thrust levels and mass utilization were low, indicating a wide spread of plasma particle velocities.

Having satisfactorily achieved these initial goals, we are now seeking to measure more quantitatively the operating characteristics of improved experimental geometries with the intent of deducing this system's feasibility as a propulsion

system. It is also hoped that the processes by which the plasma is accelerated by and ultimately leaves the magnetic field can be attacked theoretically. The status of these new experimental and theoretical efforts will be discussed.


CYLINDRICAL WAVEGUIDE, CARRYING MICRO-WAVE ENERGY (AT FREQUENCY w) FROM AN r-f GENERATOR TO THE ACCELERATOR.
COIL, WHICH GENERATES THE D-C MAGNETIC FIELD (REPRESENTED BY DASHED LINES).
GAS, INITIALLY UN-IONIZED, IS INJECTED LONGITUDINALLY INTO ACCELERATOR AT THIS POINT.
GAS INLET
A
B
ELECTRONS
IONS
ELECTRONS
REGION A: THE D-C MAGNETIC FIELD IS UNIFORM AND LONGITUDINALLY DIRECTED; ITS STRENGTH IS $B = \frac{m_e}{q_e} w$ AT ELECTRON CYCLOTRON RESONANCE. THE INJECTED GAS IS IONIZED BY THE r-f FIELD IN THIS REGION, AND THE ELECTRONS ARE ENERGIZED BY MEANS OF ELECTRON CYCLOTRON RESONANCE HEATING, THEREBY INDUCING A MAGNETIC MOMENT IN THE ELECTRON COMPONENT OF THE PLASMA.
REGION B: THE D-C MAGNETIC FIELD DIVERGES IN THIS REGION, THEREBY ESTABLISHING A LONGITUDUAL GRADIENT IN MAGNETIC FIELD STRENGTH. DUE TO THE INTERACTION OF THIS GRADIENT WITH THE PLASMA MAGNETIC MOMENT, THE PLASMA ELECTRON COMPONENT IS ACCELERATED IN THE AXIAL DIRECTION. THE ELECTRONS, IN ATTEMPTING TO ESCAPE FROM THE MAGNETIC FIELD, SET UP A LONGITUDUAL CHARGE-SEPARATION ELECTRIC FIELD WHICH ACCELERATES THE IONS IN THE AXIAL DIRECTION.

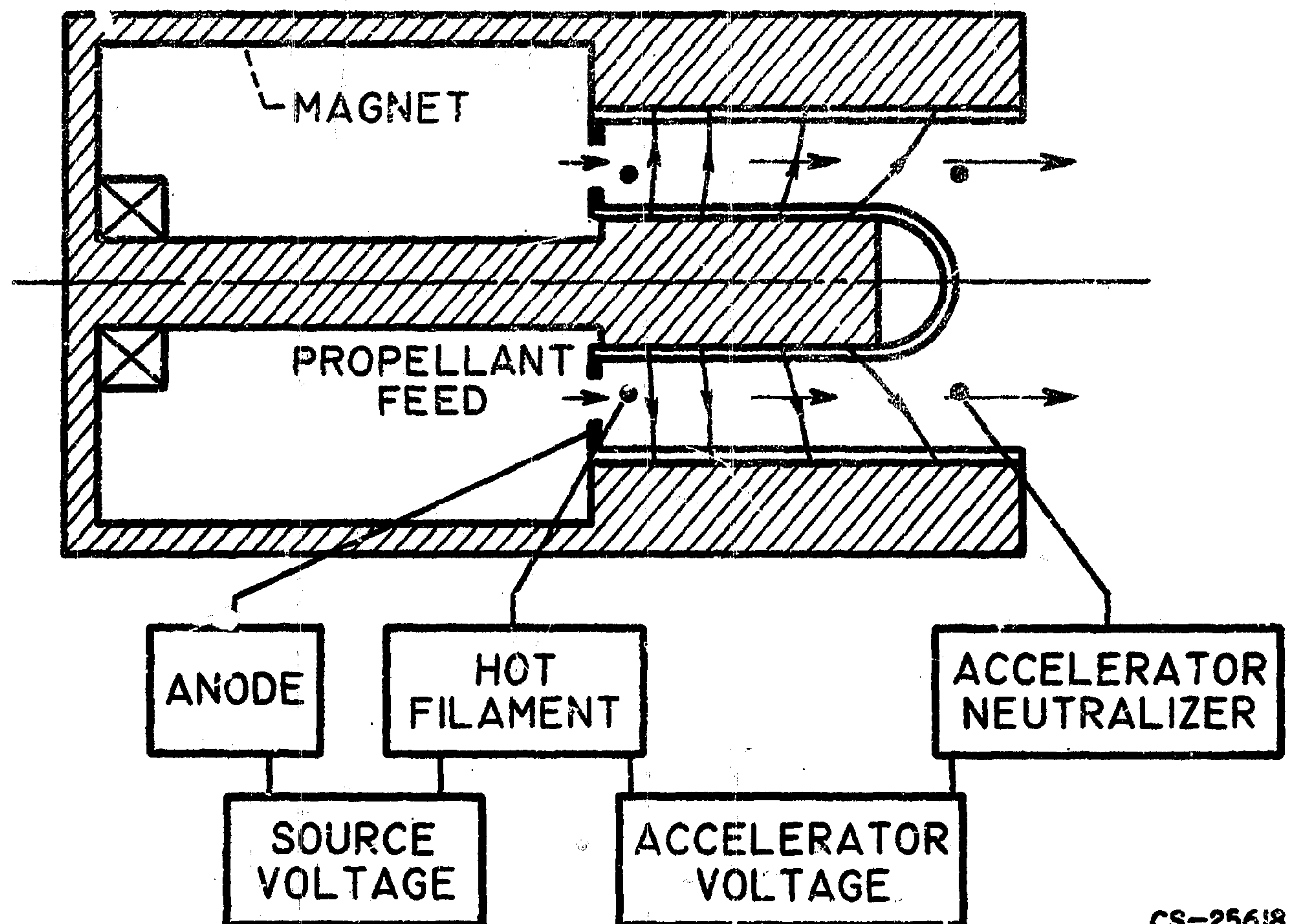
IV, 6

HALL CURRENT ION ACCELERATOR

D. L. Chubb and G. R. Seikel
NASA Lewis Research Center
Cleveland, Ohio

Experimental potential measurements through the annular Hall current accelerator have been completed for an accelerator using argon. Plasma potential variations in the axial direction were made with emitting tungsten probes. Results show that the potential variation is essentially linear through the accelerator. Also, the change in potential across the accelerator is a linear function of the magnetic field strength (for constant current and mass flow). For constant current and magnetic field strength the potential change with increasing mass flow approaches an asymptotic value.

Presently, experiments with the argon accelerator are being made to determine the electron temperature and number density. Probe techniques are being used to make the measurements. Knowing the dependence of number density, electron temperature, and electric field on the magnetic field strength, it will be possible to determine whether the axial electron diffusion obeys the classical $1/B^2$ expression. A theoretical analysis of the accelerator is in progress which is based on a three fluid model and extends our previous work by considering an energy balance of joule heating and ionization. Preliminary results of this classical calculation are in tentative agreement with experiment. The apparent dilemma between experiment and classical theory for the variation of accelerator potential with magnetic field is explained by noting that the ionization is a result of the joule heating. Therefore, as the magnetic field is increased and the potential increases, the ionization and electron density also increase, thus making plausible an approximately linear variation of potential with magnetic field. Preliminary results of this project were presented at the Fourth Symposium on Engineering Aspects of MHD. Additional experiments aimed at producing a high efficiency accelerator are being planned.



HALL CURRENT ION ACCELERATOR

IV, 7

THE HALL CURRENT ACCELERATOR

G. L. Cann
Electro-Optical Systems, Inc.
Pasadena, California
NAS 33568

A theoretical and experimental investigation has been made of the operation of a relatively novel type of plasma accelerator - the Hall Current Accelerator. This device employs the radial component of a fringing magnetic field, and the Hall induced current of an axial discharge to obtain the electromagnetic acceleration of a neutral plasma.

A theoretical determination is made of the net accelerating force per unit volume exerted upon the plasma. On the basis of a three particle gas kinetic theory, exact equations for the three components of the accelerating force are derived. The axial force component, which is predominant, is shown to be equivalent to the electrostatic acceleration of the ions, the electrons being "trapped" by the applied magnetic field. It can also be shown to be equivalent to the Lorentz force resulting from the cross product of the Hall induced aximuthal current and the applied radial magnetic field, hence the name Hall Current Accelerator.

The mechanisms by which energy is transferred from the electromagnetic field to the gas is also studied. It is found that the energy is transmitted to the gas through the acceleration of the ions only and that the electrons do not receive any appreciable energy directly from the field.

Having derived the relations for the electromagnetic force and energy transfer rate per unit volume, a gas dynamic analysis is made. Regimes of operation for a constant area accelerator are outlined, showing the importance of the critical parameters of Mach numbers and ion slip ratio. Integral solutions are obtained showing that arbitrarily high velocity ratios across the accelerator are obtainable. Expressions for the thrust efficiency are obtained and evaluated. The performance capability of an ideal Hall accelerator is compared with that of an ideal crossed field (or JxB) accelerator and it is shown that the Hall accelerator has many potential advantages over the JxB device.

Knowledge of the plasma properties is necessary for the theoretical evaluation, particularly $\omega_e\tau_e$ and $\omega_I\tau_I$. Since

adequate data was not available, the values of these Hall parameters were computed for argon and helium, the expellants of primary interest. From this data, performance curves were computed showing the velocity increments available per unit length of the accelerator and also the effective electrical conductivity of the gas. Typical examples of these calculations are shown in Figs. 1 and 2. From Fig. 2 it can be seen that there are regimes in which the electric field strength varies inversely with the applied magnetic field strength, hence no special mechanism need be invoked (e.g. MHD turbulence) to explain such a relation.

Hall current accelerators of both cylindrical and annular geometries have been built and operated. An arc jet is used to generate the plasma to which momentum is added by a 2.5 inch diameter Hall device. A combination thrust target and calorimeter is used to measure the total enthalpy and momentum in the plasma stream. Tests with the cylindrical geometry showed Hall current acceleration to occur. However, since the radial magnetic field vanishes on the axis of the channel, the current would concentrate along the center line and not be effectively accelerated.

An annular geometry accelerator was built with a radius ratio of 2.4 and operated with both argon and helium plasmas. The Hall acceleration was measured under varying conditions of plasma density, magnetic field strength, and accelerator current. Velocity rates of up to 2.78 were obtained. A correlation of the experimental results with the theory are made and qualitative agreement is found.

Experiments are now being conducted to determine the energy and momentum losses that occur because of the containing walls. A schematic of the device in which these measurements are being made is shown in Fig. 3.

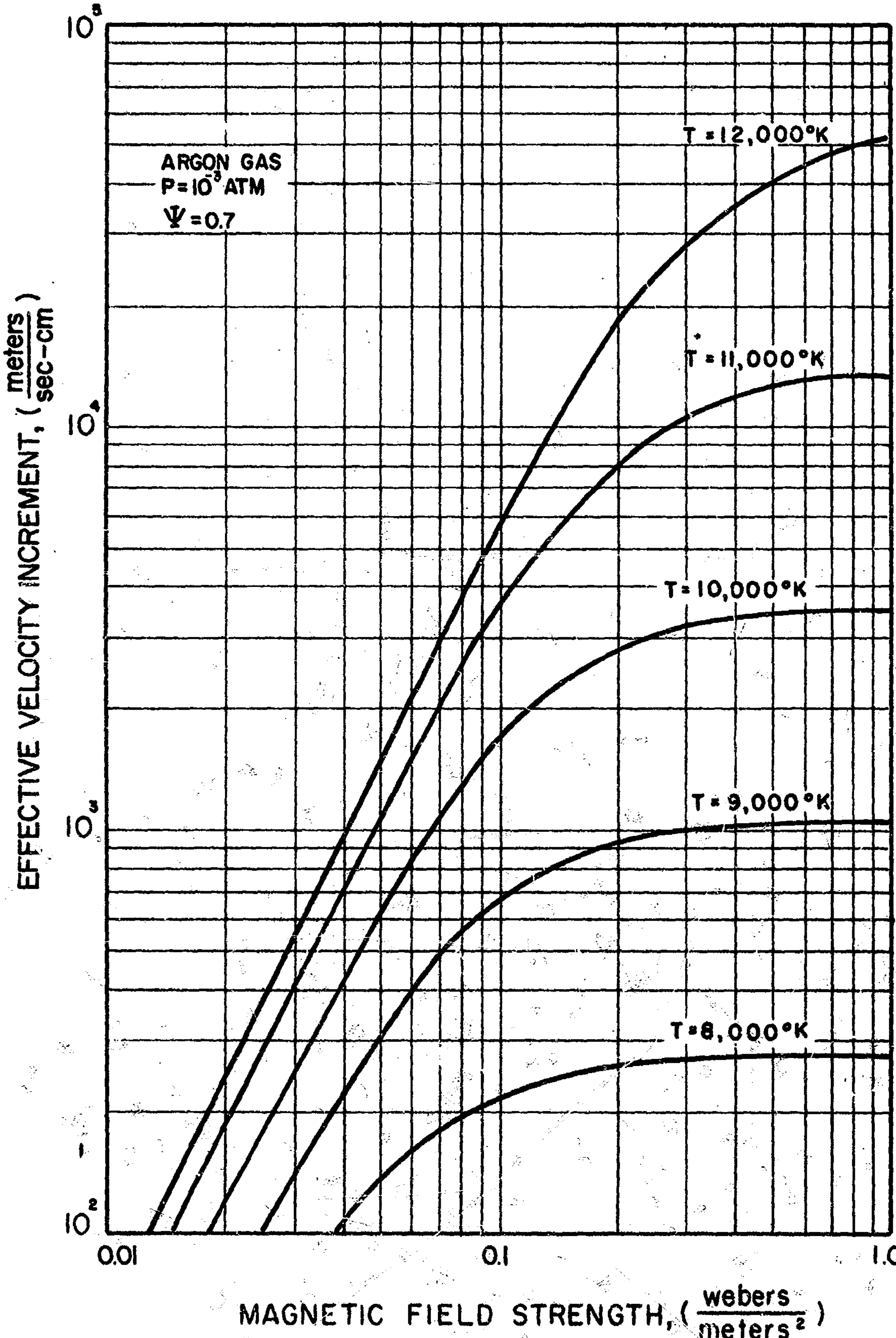


FIG. 1 EFFECTIVE VELOCITY INCREMENT PER CM OF ACCELERATOR LENGTH VERSUS APPLIED MAGNETIC FIELD STRENGTH, $P = 10^{-3}$ ATM

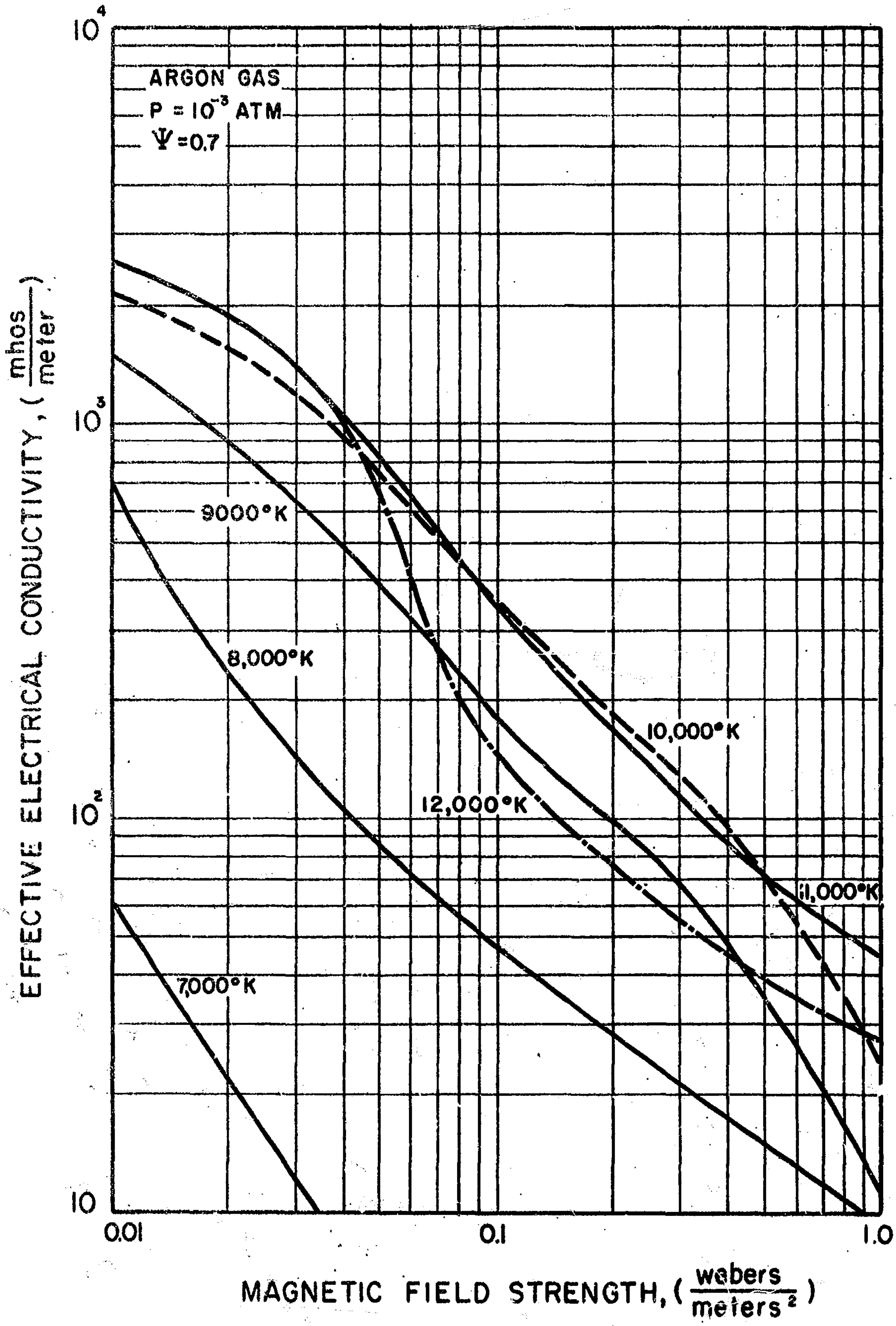


FIG. 2 EFFECTIVE ELECTRICAL CONDUCTIVITY AS A FUNCTION OF THE APPLIED MAGNETIC FIELD STRENGTH
$P = 10^{-3}$ ATM

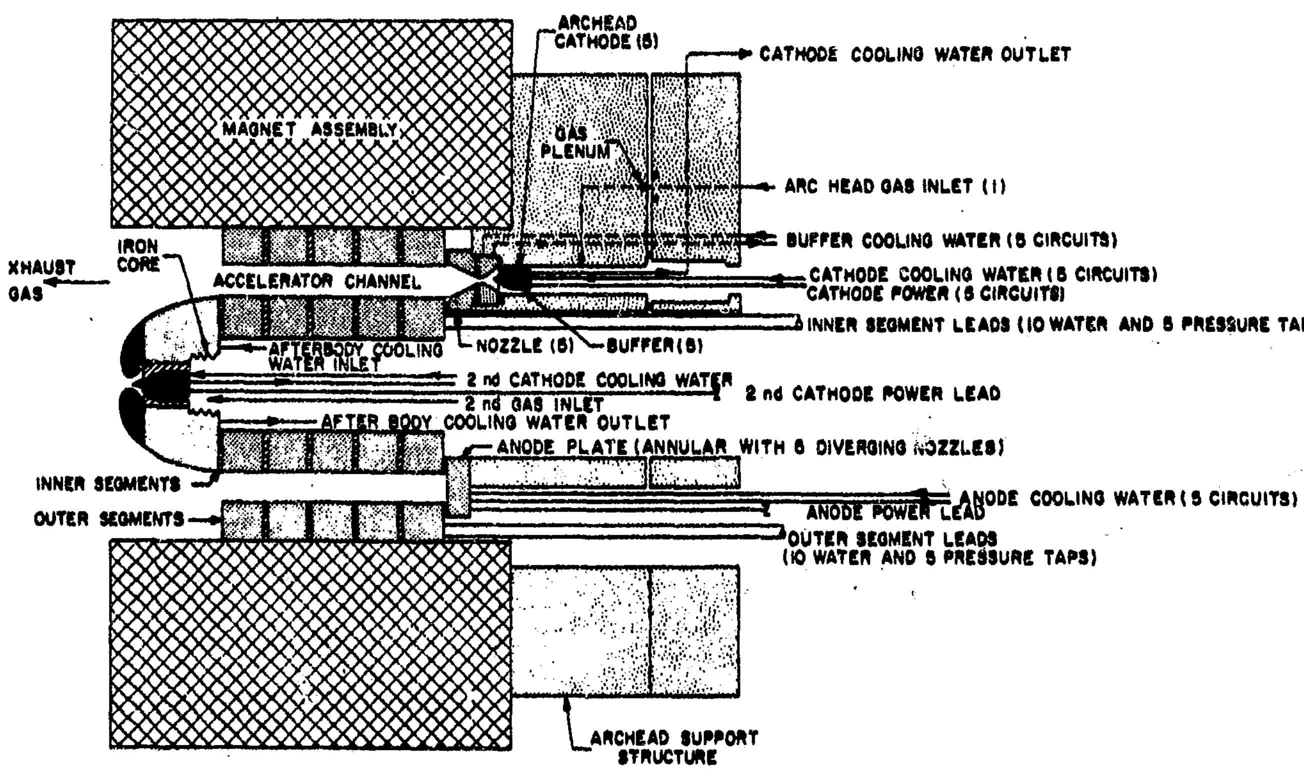


FIG. 3 HALL CURRENT ACCELERATOR SCHEMATIC

IV, 8 HALL CURRENTS AND OSCILLATIONS FOR STEADY LOW PRESSURE DISCHARGES CROSSED WITH MAGNETIC FIELDS. THEORY

Robert Hess, Philip Brockman and H. A. Hassan
NASA Langley Research Center
Hampton, Virginia

The increase to a peak and subsequent decrease of the Hall current with increasing radial field is analyzed. The influence of "ion slip" with respect to neutral atoms can explain the peak if the large charge exchange cross sections for ion-neutral encounters are considered. Nonequilibrium ionization effects are analyzed by a method originally developed by H. A. Hassan for a different discharge-magnetic field geometry discussed in another paper; results will be presented if the computer program is terminated. The meaning of the change in noise spectrum and its effect on the transition to "turbulent" conduction are evaluated. The changes in the noise spectrum with increasing magnetic field from a single peak to a spectrum with multiple peaks shifting to higher frequencies until the peaks submerge into a broad "turbulent" noise are typical of transition to turbulence. The transition spectrum of the Kadomtsev instability for magnetic fields above the critical value has been shown to be of similar nature.[1] The distinction between the observed "turbulence" and magnetohydrodynamic turbulence is briefly made and the role of the Hall effect is discussed.

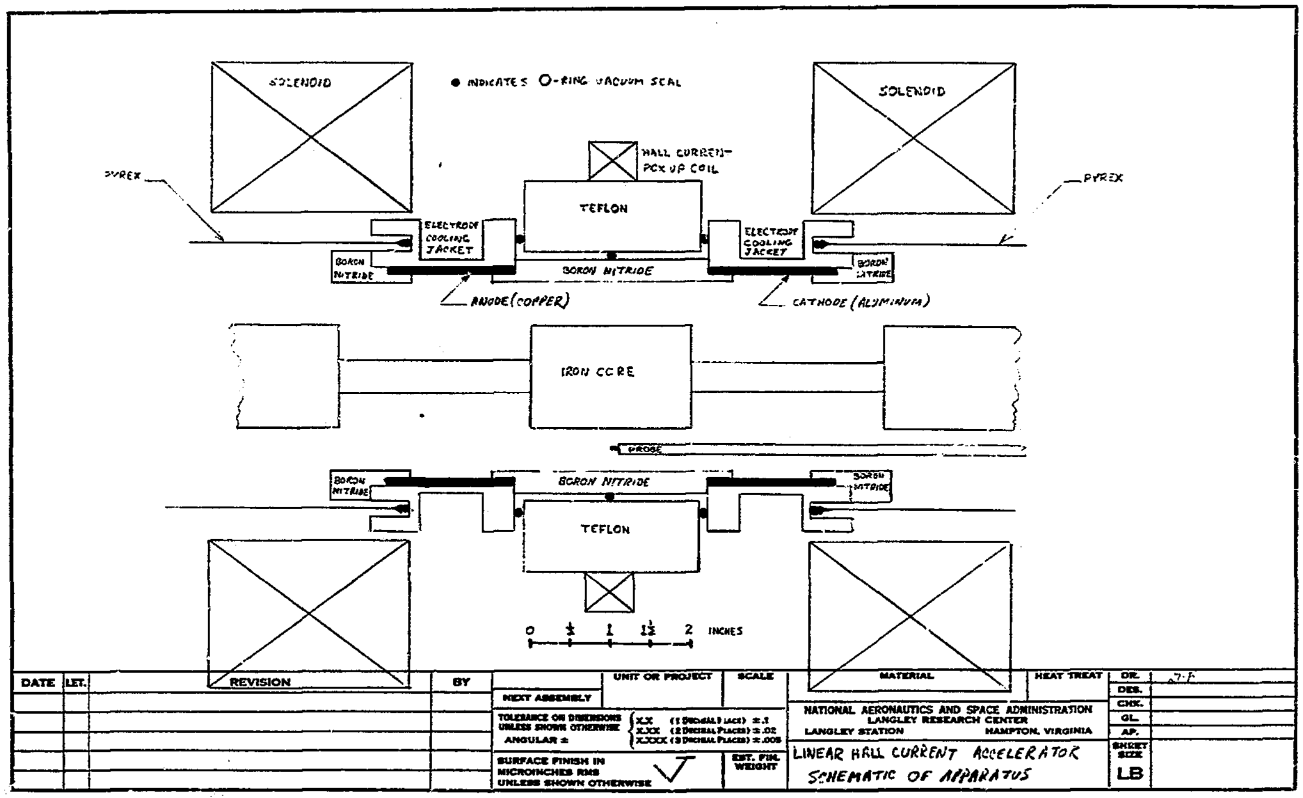
[1] Akhmedov, A. R. and Zaitsev, A. A.: Sovier Physics-Technical Physics, vol. 8, No. 2, August 1963.

IV, 9 HALL CURRENTS AND OSCILLATIONS FOR STEADY LOW PRESSURE DISCHARGES CROSSED WITH MAGNETIC FIELDS. EXPERIMENTS

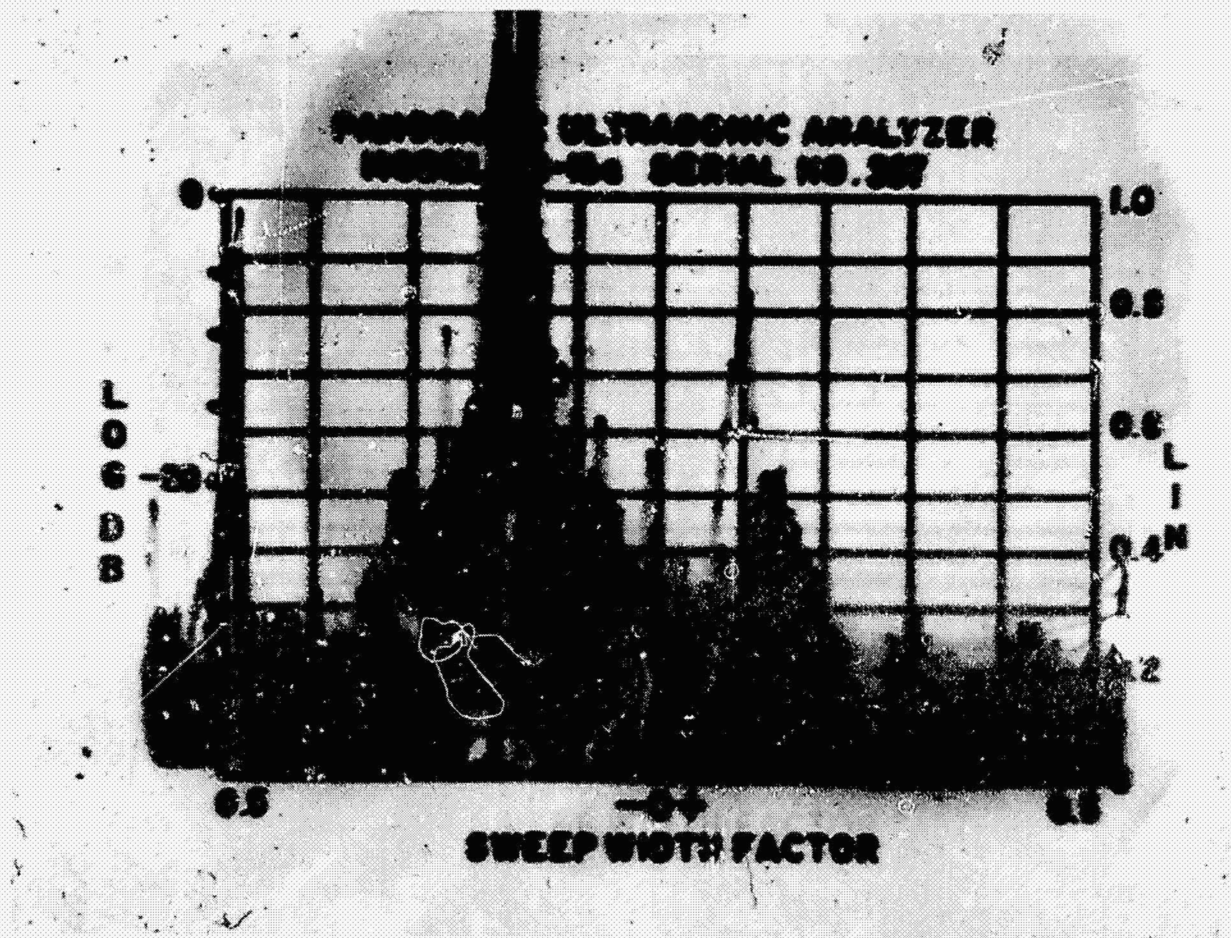
by

Barry Sidney, Joseph Burlock, Philip Brockman and Robert Hess
NASA Langley Research Center
Hampton, Virginia

The variation of azimuthal Hall currents has been measured for an axial discharge in a radial magnetic field at a variety of constant axial currents varying from 1 to 40 amperes.
Measurements in the pressure range from 30 to 8 μHg show an increase of the Hall currents to a peak with subsequent decrease followed by another smaller peak as the magnetic field increases. Measurements of the noise spectrum at constant axial currents show first the appearance of a single peak in the 5 kc range and magnetic fields from 10 to 20 gauss. With further increase in magnetic field, peaks with decreasing amplitudes appear at about harmonic frequencies, and the pattern of peaks is shifted toward higher frequencies about proportionally to the magnetic field. At high magnetic fields the peaks become submerged into the broad band noise pattern of increasing amplitude.

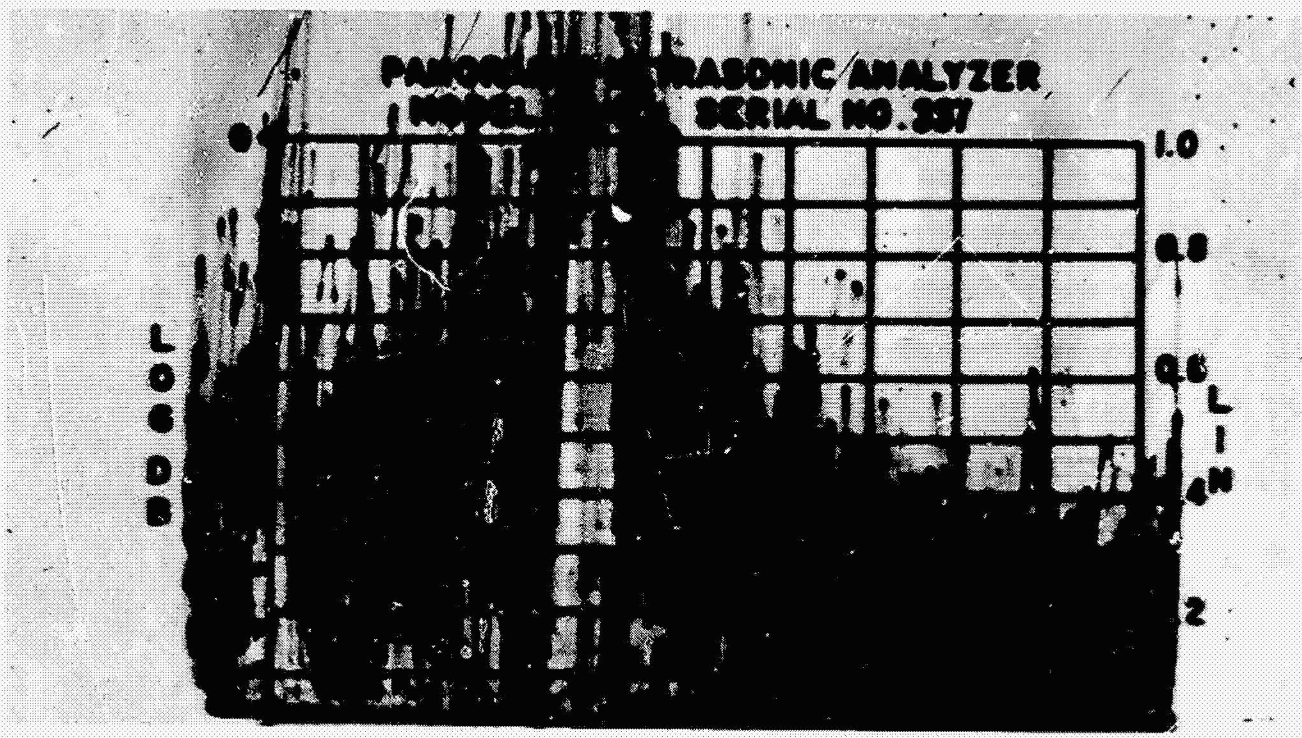


● INDICATES O-RING VACUUM SEAL
SOLENOID
SOLENOID
PYREX
PYREX
HALL CURRENT PICK UP COIL
TEFLON
ELECTRODE COOLING JACKET
ELECTRODE COOLING JACKET
BORON NITRIDE
BORON NITRIDE
BORON NITRIDE
ANODE (COPPER)
CATHODE (ALUMINUM)
IRON CORE
PROBE
BORON NITRIDE
BORON NITRIDE
BORON NITRIDE
TEFLON
0 ½ 1 1½ 2 INCHES
DATE LET. REVISION BY
UNIT OR PROJECT SCALE MATERIAL HEAT TREAT
NEXT ASSEMBLY
TOLERANCE ON DIMENSIONS UNLESS SHOWN OTHERWISE
ANGULAR ±
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
LANGLEY STATION HAMPTON, VIRGINIA
SURFACE FINISH IN MICROINCHES RMS UNLESS SHOWN OTHERWISE
EST. FIN. WEIGHT
LINEAR HALL CURRENT ACCELERATOR
SCHEMATIC OF APPARATUS
DR. DES. CHK. GL. AP.
SHEET SIZE
LB



AMPLITUDE, ARBITRARY UNITS

FREQUENCY TRANSITION TO TURBULENCE



AMPLITUDE, ARBITRARY UNITS

FREQUENCY TURBULENCE

V, 1

ELECTROMAGNETIC WAVE PROPAGATION IN MAGNETOPLASMAS

D. A. Huchital
Rensselaer Polytechnic Institute
Troy, New York

NsG 48-60

A theoretical and experimental research program on properties of magnetoplasmas is being pursued at Rensselaer. Following the cross section measurements described in the paper by Stotz, and the initial work in the magnetoplasma area, described in the paper by Holt, Haskell and Mendell, the present objective is the measurement of transport coefficients in a plasma in the presence of a magnetic field.

The plasma analysis is accomplished by application of the microwave polarization techniques developed in this laboratory. The plasma parameters are determined from the knowledge of the magnitude of the vertical, horizontal, and right and left circular components of both input and output waves. A method for the simultaneous display of these quantities has been developed.

The plasma will be studied in a guided wave configuration where the plasma cell constitutes a section of the microwave circuit. This situation has a considerable advantage in the fact that the microwave fields are completely defined at the plasma-waveguide boundary. A theoretical study of the resulting boundary value problem has been made for propagation parallel to the magnetic field. The solution to a fourth order differential equation in the longitudinal components of the fields determines their transverse components. Application of simple boundary conditions yields a determinental equation in the propagation constant which is solved simultaneously with the dispersion relation.

In addition a critical study of the usual theoretical formulation of the problem of electromagnetic wave propagation in magnetoplasmas has been made[1]. The assumption that free electrons oscillate at the signal frequency has been examined and found to be generally invalid for an anisotropic plasma.

1. D. A. Huchital, "On the Existence of Cyclotron Frequency Waves in a Cold, Collisionless, Anisotropic Plasma", Rensselaer Polytechnic Institute, Plasma Research Laboratory, Tech. Rpt. No. 10, Aug. 1963.

The rigorous solution for the particle trajectories is shown to imply the existence of a mode of propagation at the cyclotron frequency driven by the wave at the signal frequency. This mode has been named the "H" (for Hybrid) mode. The expected characteristics of this mode of propagation are presented, and its significance, especially in the case of wave propagation near cyclotron resonance, is described. It is shown that in this case the H wave may be considerably enhanced at the expense of the signal frequency wave.

V, 2

MICROWAVE CAVITY MEANSUREMENT OF THE FARADAY EFFECT IN A GLOW DISCHARGE PLASMA

F. R. Crownfield, Jr.
College of William & Mary
Williamsburg, Virginia

NsG 106-61

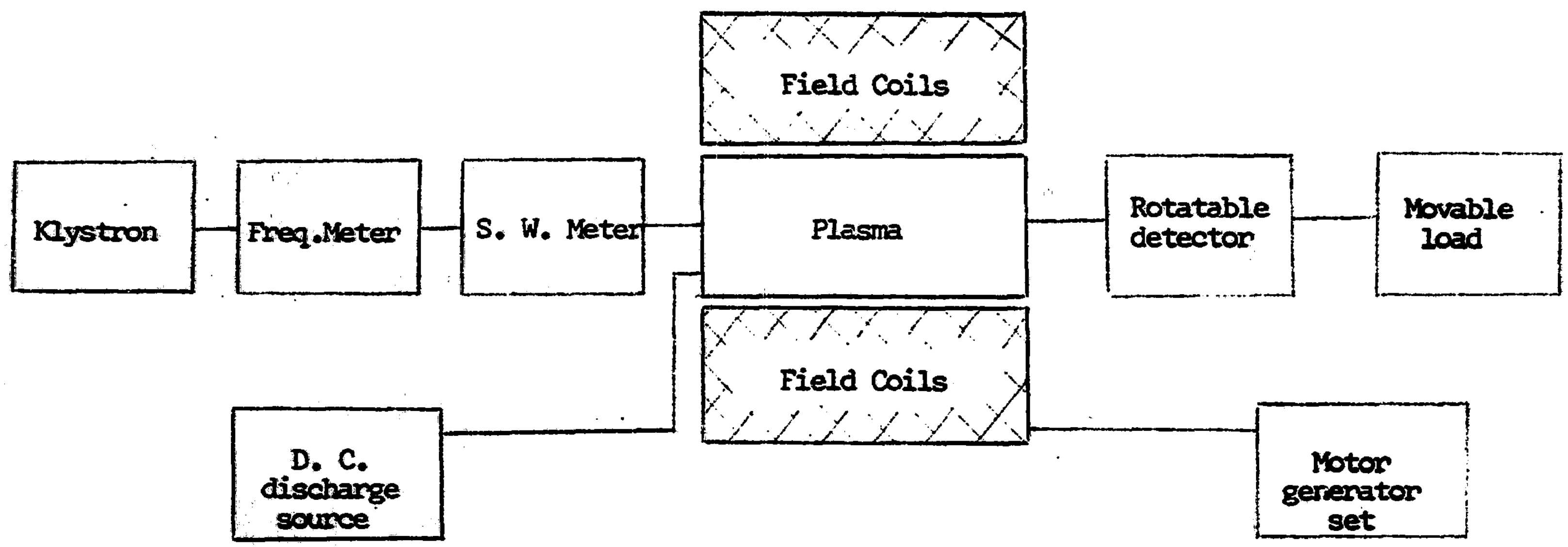
We have observed the coupling of the orthogonal, linearly polarized, TE_{111} modes of a right cyclindrical cavity due to the Faraday Effect in a coaxially located neon glow discharge. Measurements as a function of applied magnetic field are interpreted in terms of a simple theory to yield an effective electron collision frequency. The values of the collision frequency obtained in this way are greater than predicted from the momentum-transfer collision cross-section. Some data showed anonalies near harmonics of electron cyclotron resonance, but these data were not reproducible.

V, 3 GUIDED WAVES IN AN ANISOTROPIC PLASMA

A. M. Ferendeci
Case Institute of Technology
Cleveland, Ohio

NsG 198-62

Microwave propagation in a one inch circular wave guide completely filled with plasma, subjected to an external d.c. magnetic field is experimentally investigated. Propagation constant, phase velocity and the cut-off frequency of the microwave field in a cylindrical wave guide are derived from Maxwell's equations using the tensor dielectric constant for a cold plasma. The effects of the plasma density and the d.c. magnetic field on the different constants of the TE_{11} limit mode are fully investigated. The steady state plasma is produced by a hot cathode discharge of argon gas at 0.1 mm Hg. The phase velocity and the propagation constant is experimentally determined from the measurements of the Faraday rotation of the plane of polarization of the microwave field and the standing-wave ratios that are set up in the waveguide against the externally applied magnetic field. The d.c. magnetic field can be increased to obtain cyclotron frequencies greater than the microwave frequency that is used for the measurements. From the experimental data of the cut-off frequency of the TE_{11} limit mode, one can calculate the average density of a plasma in a circular waveguide. The schematic of the experimental set-up is shown in the diagram below.



Field Coils
Klystron
Freq.Meter
S. W. Meter
Plasma
Rotatable detector
Movable load
Field Coils
D. C. discharge source
Motor generator set

V, 4

PROPAGATION AND DISPERSION OF HYDROMAGNETIC AND ION CYCLOTRON WAVES IN PLASMAS IMMERSED IN MAGNETIC FIELDS

A. A. Dougal
The University of Texas
Austin 12, Texas
NsG-353

Analysis of radially propagating waves in a bounded magnetoactive plasma was initiated. The configuration is that of a partially ionized plasma slab, bounded by two infinitely large conducting plates of finite separation. The plates may be in direct contact with the plasma, or insulated from it by thin layers of dielectric materials. A static magnetic field is imposed upon the plasma in a direction normal to the plates. A current source with an arbitrary current distribution is postulated in the plasma to excite waves. The presence of magnetic fields in plasma volumes results in a dyadic electrical conductivity. In this work, the wave equation becomes a dyadic-vector Helmholtz equation. Separability was studied to facilitate fitting of boundary conditions. It was found that four coordinate systems, rectangular, circular cylindrical, elliptic cylindrical, and parabolic cylindrical permit separation of the dyadic-vector Helmholtz equation into terms of longitudinal and transverse vector components. The longitudinal and transverse vectors are generated by differential vector operations on scalar functions, each of which satisfies a scalar Helmholtz equation. A Green's dyadic is generated from vector eigenfunctions to make possible solutions to the inhomogeneous wave equation applicable to sources in the plasma region. The formulation developed in this work was applied to two different current sources. One current source is that of a uniform line current placed at the origin. The second is that of a uniform circular loop current placed at the origin. The radial propagation of the electric and magnetic fields was determined for both sources. Evaluation of the Poynting vector was pursued to determine the source radiation resistance. The solutions determined for the finite boundaries were checked in the limit as the boundaries are permitted to recede to infinity.

An experimental investigation of current sheath dynamics and magnetosonic oscillations in magnetoplasmas was initiated. The dynamical behavior of a current sheath formed in a preionized hydrogenic plasma, accelerated by $\bar{J} \times \bar{B}$ forces, and moving through a steady stabilizing magnetic field is being studied. An experimental arrangement using a stabilized inverse pinch was designed, fabricated, and placed successfully

in operation. The experimental arrangement has utility for investigating current sheath dynamics, the possible onset of magnetosonic oscillations, and finite resistivity instabilities in an otherwise stable configuration. The experimental arrangement is characterized by: a metal and glass inverse pinch discharge tube of approximately four inches length and seven inches diameter with an insulated solid conductor on the central axis; a preionization capacitor discharge unit; a main accelerator capacitor discharge unit; a pole type electromagnet to supply the stabilizing field; a vacuum and gas filling system; mechanical and electronic control circuits; and oscilloscopes and electronic metering circuits. In the initial experimentation, plasma diagnostics were accomplished both by the use of magnetic probes and ultra high speed Kerr cell photography. Magnetic probes consisting of small coils of twenty turns of wire on a fifty mil diameter form provide data on the magnetic field components from which the dynamical behavior of the current sheath is determined. The magnetic probes also apply to the study of the onset of magnetosonic oscillations and resistive instabilities. The utilization of simple mirrors and lenses with the ultra high speed Kerr cell camera system has made possible high speed photographic recording of the plasma sheath dynamics in this experimental configuration. Experimental observations show that a reproducible current sheath is formed in the preionized hydrogenic gas by the main capacitor discharge. The formation and dynamical motion of the current sheath have been determined for a wide range of hydrogenic gas pressures, and for a wide range of stabilizing magnetic fields. Presently, with higher peak discharge currents in excess of 100,000 amperes, a search is in progress for the onset of magnetosonic oscillations, and the onset of finite resistivity instabilities.

Experimental investigations of <u>ion resonances and ion cyclotron wave propagation in one- and two-ion species plasmas subjected to intense magnetic fields</u> are of interest in this work. The principal plasma effects of interest include: The propagation and dispersion of hydromagnetic and ion cyclotron waves under the action of resonant (parent) and nonresonant (impurity) ion-ion interaction; polarization characteristics of propagated waves; effects of ion_1^+ - ion_2^+ collisions on resonances in a two-ion species plasma; and the influence of plasma sheaths on ion cyclotron resonance to determine the effects of ion trajectories intersecting plasma sheaths. The design of a major experimental arrangement for this experiment for this experimental research was completed and fabrication of the requisite instrumentation is rapidly nearing completion. The experimental arrangement is characterized by: a solenoidal DC magnetic field system with seven inch bore to produce magnetic fields up to 11,000 gauss; a prime DC power supply of 100 KW, consisting of a motor generator set, and an electronically controlled Amplidyne regulator system; an RF excitation system consisting of a pulsed crystal controlled

transmitter, kilowatt linear amplifier, and a 25 KW driver; a "Stix Coil" to couple the RF drive power onto the plasma column; a plasma tube of one meter length and 64 mm diameter; a demountable vacuum and gas filling system; and electronic pulse timing and oscillography equipment. In addition, an alkali metal vapor plasma tube was designed to produce plasma by contact ionization in the vapor mode. Parallel development of plasma diagnostic methods has been in progress. RF magnetic probes were designed to provide information on wavelength, polarization, damping of an axially propagated wave, and the RF field distribution. A diamagnetic probe method has been evaluated to provide information on plasma electron density and temperature. RF power input to the plasma is accessible through simultaneous recording of the "Stix Coil" input voltage and current.

V, 5

THE ABSORPTION OF VERTICALLY POLARIZED PLANE ELECTROMAGNETIC WAVES IN THIN SLABS OF PLASMA

P. D. Rowley
NASA Ames Research Center
Mountain View, California

Obliquely incident vertically polarized (TM) plane electromagnetic waves may be strongly absorbed by thin plasma slabs under certain conditions. An approximate analysis for the case of a thin uniform plasma slab backed by a conductor is given. It is shown that for this absorption effect to occur for this case the collision frequency must not be zero but may be small and maximum absorption occurs when the frequency is slightly greater than the plasma frequency. The relations between the frequency, the collision frequency, the plasma frequency, the angle of incidence, and the slab thickness are given where two of these quantities are dependent variables. The validity of this approximate analysis is discussed. This absorption effect may occur in isolated thin plasma slabs and in multiple plasma slabs. The multiple thin slab approximation to the problem of the interaction of a vertically polarized plane wave with a plane stratified plasma region having a continuous electron density profile is usually poor when the collision frequency is small although it is a suitable method for plasma regions with a sufficiently large electron density. Numerical calculations of the reflection coefficient for a number of thin plasma slab cases are given which illustrate the effect.

V, 6

CHARACTERISTICS OF A MAGNETICALLY CONFINED STEADY STATE PLASMA BEAM

D. A. Meskan & R. E. Collin
Case Institute of Technology
Cleveland, Ohio
NsG 198-62

The results of measurements on a steady state cylindrical plasma beam which is produced by a reflex discharge are presented. Spectroscopic and Langmuir probe measurements indicate a beam ion density greater than 10^{12} cm^{-3} and a relatively low impurity density. Electrons with energies up to about twenty electron volts appear to be present. Quasi periodic disturbances which are believed to be characteristic of the reflex discharge have been observed.

These results indicate that a theoretical model for ion wave phenomena in this type of beam should include the possibility of different ion and electron temperatures and drift velocities. An attempt is being made to use Hankel transforms to solve an idealized boundary value problem which includes these effects.

Experimental verification of the suitability of the model is a primary objective for future experiments.

V, 7

REFLECTION OF AN EM-WAVE FROM A SHOCK FRONT

W. H. Eggimann
Case Institute of Technology
Cleveland, Ohio
NsG 198-62

Velocity measurements: The velocity of a moving shock-front is determined from the frequency shift of a reflected EM-wave. In order to measure the frequency continuously the set-up in Fig. 1 was used. The Doppler frequency is amplified and clipped, a pulse generator is triggered by the positive half wave and the negative pulses are subsequently integrated. The resulting signal is displayed on an oscilloscope. It is easily seen that the trace gives directly the position of the shock as a function of time, so that the velocity is equal to the slope of the curve. The photograph shows the trace X(t) at the top and the Doppler signal Δf at the bottom. (Figure 2).

Measurement of the density profile of a shock: EM-waves are totally reflected from a plasma shockfront if the density n (in m^{-3}) is larger than $n_f = 0.0124f^2$, where f is the frequency of the wave in cps. From the standing wave pattern the location of the point of this critical density in the shock can be deduced, provided the density profile is known. Reflection patterns for step-, ramp-, exponential and other profiles have been computed analytically and with the help of an analog computer. Using waves of different frequencies, all this information leads to an estimate of the density profile and the shock thickness. Experiments with 3 cm and 1 cm waves are under way.

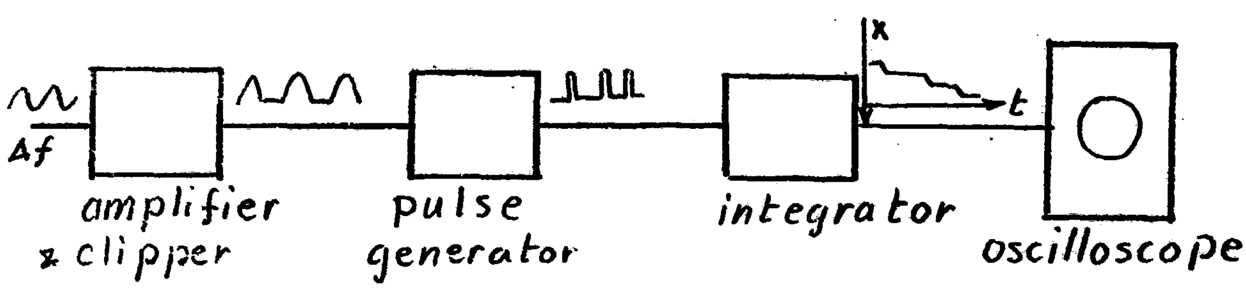


Fig. 1: Frequency measuring apparatus

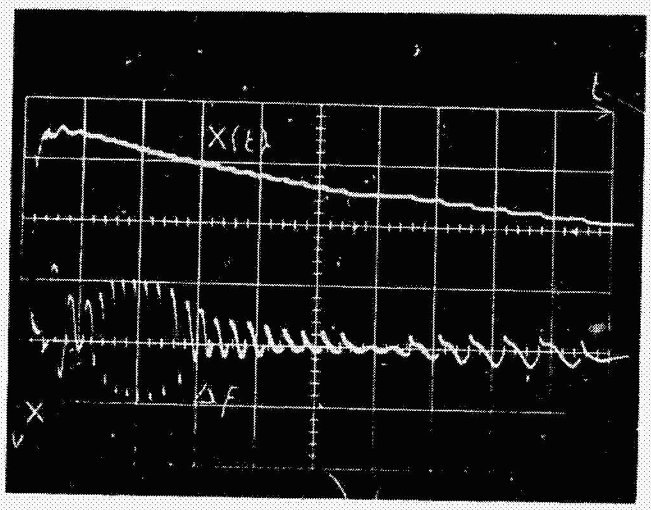


Figure 2. Position of shock X(t) and Doppler signal Δf as a function of time

V, 8

ELECTROMAGNETIC WAVE COUPLING TO MAGNETIZED PLASMAS

The Electromagnetic Research Corporation
College Park, Maryland

V, 9

INTERACTION OF PLASMA OSCILLATIONS WITH CONDUCTION IN A PENNING GAUGE

F. R. Crownfield, Jr.
College of William and Mary
Williamsburg, Virginia
NsG 106-61

We have observed oscillations at VHF in a Penning Gauge operating at pressures of the order of one micron of mercury in magnetic fields of about 200 Oersteds. The oscillations occur only for certain values of the anode voltage, and concurrent with the oscillations anomalies are observed in the current vs. voltage characteristic of the gauge. This behavior clearly indicates an interaction between these oscillations and the conduction mechanisms in the gauge. An interpretation of the nature of the oscillations and a discussion of their excitation is presented. The details of the interaction are not yet fully understood.

V, 10

TRANSVERSE TRAVELLING WAVE PLASMA ENGINE *

L. Heflinger, A. Schaffer
General Technology Corporation
Torrance, California

The engine under development employs a transverse travelling magnetic field created by four coils supplied from a megawatt level 2-phase oscillator. The engine operates in the region of small mean free path at magnetic field strengths from 200 to 1000 gauss and phase velocities from 30,000 to 70,000 meters per second. Electrical energy and propellant are supplied continuously, yielding a steady-state operation for the duration of the run, which is at present one millisecond. No auxiliary ionizer is required.

Primary performance measurements consist of propellant mass, impulse, and energy input, each totalled over the duration of the run. The impulse measured is the electromagnetic back reaction on the drive coils, which are suspended as a ballistic pendulum. Probes and high speed photographs are used to diagnose the plasma behavior.

Results to date include measurements of mass and impulse, yielding values for thrust, specific impulse, and plasma directed kinetic energy. For example, at one operating condition (argon, 225 gauss, 50,000 meters per second phase velocity) measurements showed thrusts of about 1/10 pound at a specific impulse of 4000 seconds. Efficiency measurements are in progress with recently developed energy input diagnostics.

*Post deadline paper

VI. 1 STABILITY OF MAGNETOHYDRODYNAMIC CONFIGURATIONS

E. Reshotko
Lewis Research Center
Cleveland, Ohio

The disturbance equations for incompressible parallel flows in an electrically conducting fluid have been derived for flowing, current carrying configurations. It is shown that the stability characteristics of an incompressible three-dimensional parallel flow configuration to a plane wave disturbance of arbitrary orientation are determined by the solution to a two-dimensional problem governed by the components of the mean velocity and magnetic fields in the direction of wave propagation and by the transverse magnetic field. The resulting differential equations are a coupled sixth-order set for the disturbance velocity field and magnetic field and may be solved by exact numerical techniques.

An energy relation synthesizing the prior results of Stuart and Kovasznay is obtained for the net rate of change of disturbance energy E.

$$\frac{DE}{Dt} = \int\left(-\rho\overline{v_\xi v_y} + \frac{\overline{b_\xi b_y}}{\mu}\right)\frac{dV}{dy}\,d\tau + \int\left(\frac{\overline{v_\xi b_y} - \overline{v_y b_\xi}}{\mu}\right)\frac{dB_\xi}{dy}\,d\tau - \int\rho\nu\overline{\left(\frac{\partial v_y}{\partial \xi} - \frac{\partial v_\xi}{\partial y}\right)^2}\,d\tau - \int\frac{\overline{j'^2}}{\sigma}\,d\tau$$

where

$$E \equiv \frac{1}{2}\left[\rho\,\overline{(v_\xi^2 + v_y^2)} + \frac{\overline{b_\xi^2 + b_y^2}}{\mu}\right]$$

ξ is the coordinate in the direction of wave propagation

y is the normal coordinate

This relation shows that energy may be transferred from the basic configuration to the disturbances by the action of Reynolds stresses and magnetic shear stresses in a configuration having mean vorticity. For current carrying configurations such energy transfer is related to the component in the direction of the mean current of the time-independent correlation electric field set up by the disturbances. Disturbance energy is of course decreased through viscous and joule dissipation. A direct analogy between the viscous and magnetic terms is evident upon identifying the current as the "vorticity" of the magnetic field. An estimate of the orders of magnitude of the terms in the energy relation indicates that for small viscosity and resistivity, the disturbance energy produced may exceed that dissipated leading to instabilities not present in an ideal fluid.

VI, 2 STRUCTURE OF SHOCK WAVES IN COLLISION-FREE, TEPID PLASMAS

W. P. Jones and V.J. Rossow
NASA Ames Research Center
Moffett Field, California

The particle motions and electromagnetic fields caused by a magnetic compression wave passing through a fully ionized, collisionless plasma embedded in a magnetic field has been studied for a discrete, one-dimensional model by means of a numerical analysis on an electronic computer. Computations made by previous authors for a model that assumes the ambient gas to be cold (i.e., zero temperature) indicate that for low and high Alfven Mach numbers the magnetic compression waves can be classified into two separate regimes: (a) one consists of a series of equally spaced waves of increasing amplitude that propagate without changing form; and, (b) the other is characterized by the development first of a single large wave whose form then changes continuously as it propagates. Transition from one regime to the other occurs at an Alfven Mach number of about two. The present work shows that such a classification becomes obscure when the initial plasma temperature is tepid. Highly ordered wave structure found for the cold plasma when the Alfven Mach number is less than two, is destroyed everywhere except near the front of the propagating disturbance when the plasma is warm. Also, when the Alfven Mach number is greater than two, the development of the single strong pulse, observed when the plasma is initially cold, is retarded when the initial plasma state is tepid.

A presentation will be made of results for the two cases in which the ambient plasma temperature is cold and tepid in the form of three-dimensional plots of magnetic field vs. distance and vs. time for representative values of the characteristic parameters.

VI, 3

HYPERSONIC MAGNETOHYDRODYNAMICS

R.H. Levy, E.V. Locke, H.E. Petschek, and P.H. Rose

AVCO-Everett Research Laboratory
Everett, Massachusetts

NASw-748

A low magnetic Reynolds number high β flow in a simple geometry has been studied theoretically[1] and experimentally. The magnetic field is that due to a current carrying wire and the flow is two-dimensional. A shock wave stands ahead of the wire and is nearly coincident with a field line. The flow takes place in a thin layer behind this shock. The position of the shock layer is found by setting an interaction parameter based on the velocity behind the normal shock and the thickness of the shock layer equal to a number which analysis shows to be about 1/3.

The experiment was performed in air in an electrically driven shock tube, using a shock speed of 8 mm/μsec and an initial pressure of 250 μHg. Currents up to 2.8×10^5 amps were pulsed through the wire using a capacitor bank having a quarter cycle time of 40 μsec. The predicted shock position was about 2 cm from the wire. The experimental and theoretical shock layer positions are shown on Fig. 1.

Theoretically the currents in the gas which flow in the shock layer antiparallel to the current in the wire are supposed to close on themselves; this is impossible in the experiment and an attempt has been made to measure the electric field associated with their closing. Another theoretical prediction is that since there is no hot gas flow behind the shock layer, the convective heat transfer to a surface in this region should be nil. It is planned to use the infrared gage developed by Camac[2] to investigate this point.

A different geometry has also been studied theoretically; in this case the flow is axially symmetric. The magnetic interaction is provided by a dipole having its axis aligned with the flow. Since in this geometry there is no interaction along the stagnation streamline, a body is also required. The theory shows, however, that when a suitable interaction parameter is of the order of unity, the body exerts only a weak influence on the flow. In particular, virtually all the drag appears at the coil rather than at the surface of the body. The general features of this flow

[1] Levy, R.H. and Petschek, H.E., "The Magnetohydrodynamically Supported Hypersonic Shock Layer," Phys. of Fluids 6: 946 (July 1963).

are shown schematically in Fig. 2. Other theoretical results include the resolution of certain discrepancies appearing in the literature on this subject, and the prediction that much greater heat transfer reductions might be achieved in this geometry than had hitherto been thought possible. An experiment in this geometry is planned.

Some preliminary studies have been undertaken to relate the information on forces gained in these studies to re-entry calculations.

---

[2] Camac, M. and Feinberg, R., "High Speed Infrared Bolometer," Rev. Sci. Instr. **33**: 964-972 (Sept. 1962).

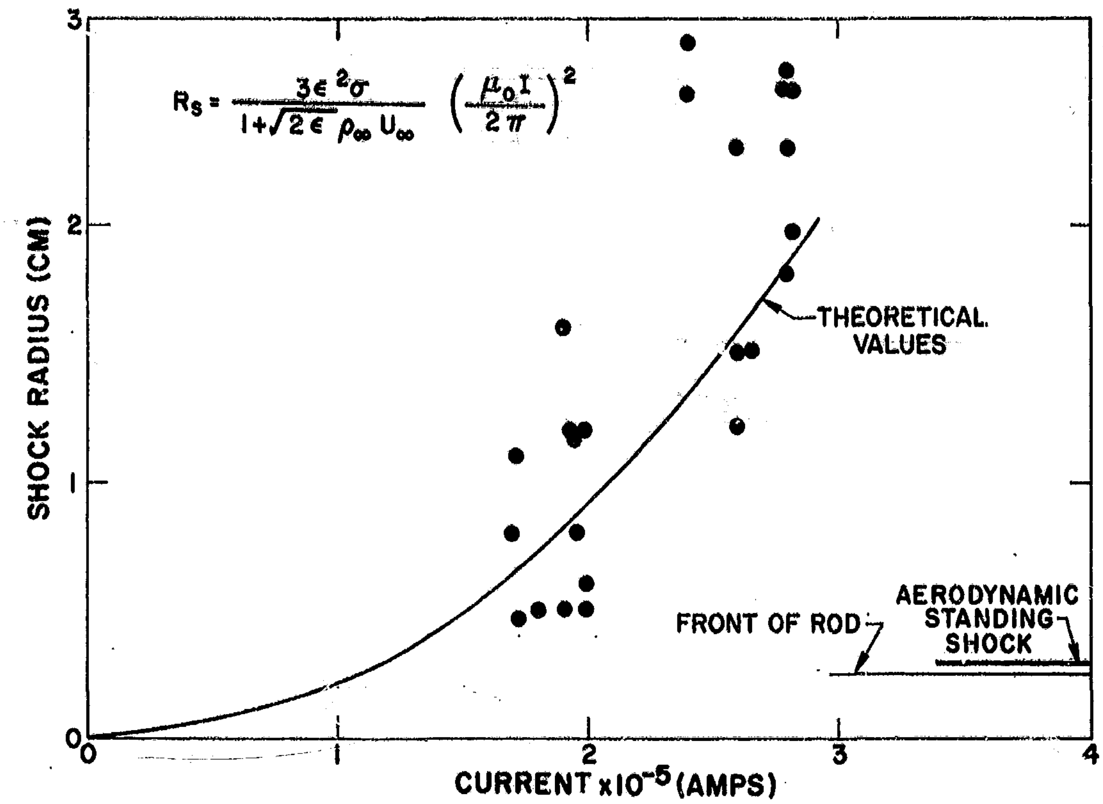


Figure 1

This figure shows the positions of the shock layer ahead of the wire, as predicted and as measured. Note the size of the rod and the position the shock would occupy if there were no magnetic interaction.

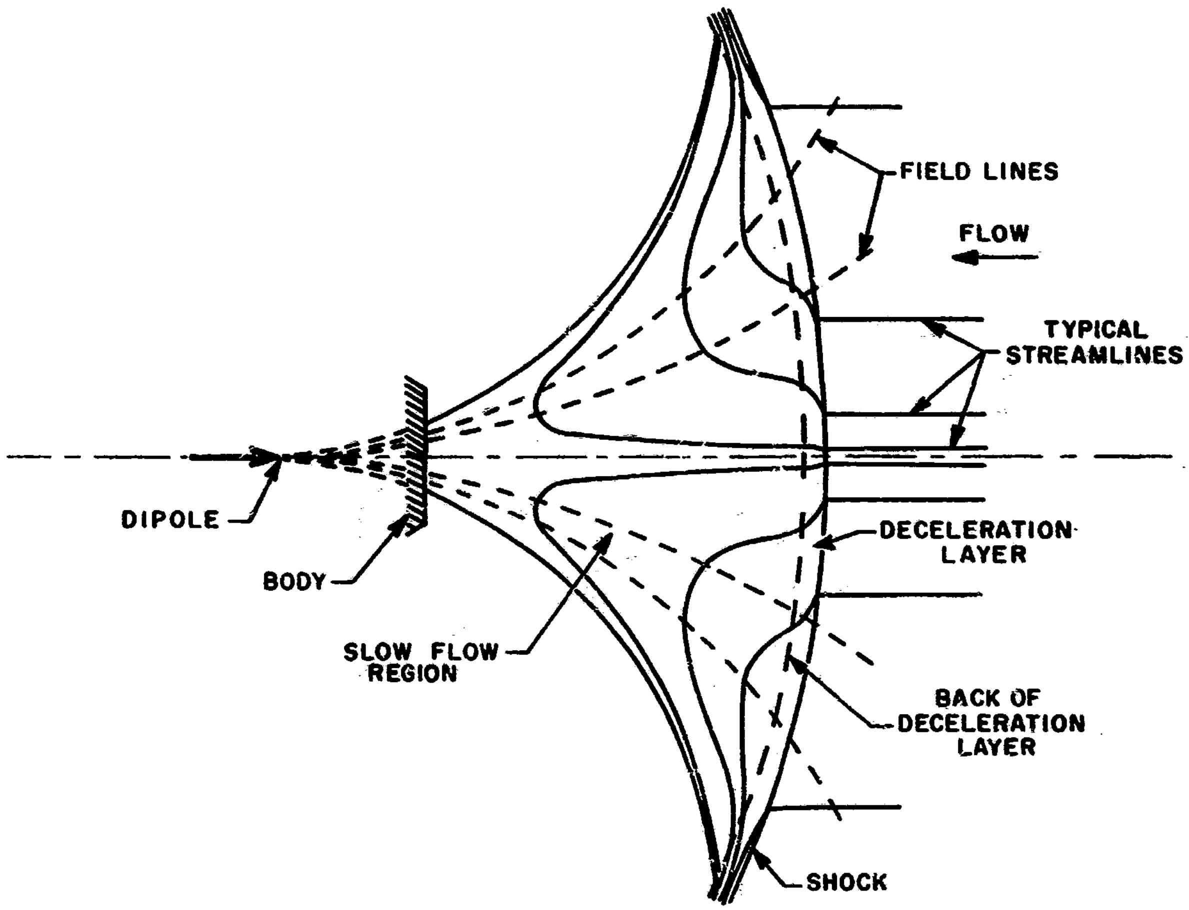


Figure 2

This figure illustrates the principal features of the theoretical model for the flow past a dipole oriented parallel to the flow. The magnetic field lines are dashed, the streamlines are solid. Note the two distinct regions of the flow and a limiting streamline beyond which the gas does not penetrate. The influence of the body on this flow is relatively slight.

VI, 4 MAGNETOAERODYNAMIC DRAG AND SHOCK STAND-OFF DISTANCE

T.P. Anderson, Ching Shi Liu, R. C. Warder, Jr. and
Ali Bulent Cambel

Northwestern University
Evanston, Illinois

Although the enhancement of reentry drag and communications by means of magnetogasdynamic effects has been known for some time, the configuration has not been exploited due to hardware design limitations. However, recent developments concerning superconducting magnets offer enhanced possibilities.

It is the purpose of this study to evaluate the validity and range of applicability of the large number of theoretical analyses concerning magnetoaerodynamic drag and shock stand-off distance. The project will be experimental in nature complemented by analyses of theoretical solutions to the problem. Thus the primary mission of the study will be to develop a systematic correlation between various theories and experimental observations obtained under various conditions.

The first phase of the proposed research would be to summarize the results of previous theoretical investigations much in the manner of the sample table.

In order to evaluate the various theoretical analyses of magnetoaerodynamic drag and shock stand-off distance, a series of experimental studies will be performed to systematically extend the preliminary studies of magnetoaerodynamic drag and shock stand-off distance initiated in the Gas Dynamics Laboratory. Simple model shapes such as the hemispherical nose with a cylindrical afterbody will be chosen for the initial studies in order to coordinate the experimental measurements with theoretical analyses. These initial studies will be performed using an argon plasma since a large amount of properties and tabular data have been accumulated concerning the thermophysical state of argon plasmas. If as a result of the experimental studies it is found that existing magnetoaerodynamic drag and shock stand-off distance theories are inadequate, specific analytical studies will be undertaken.

Once the applicable analytical treatments are determined as a result of the experimental measurements in the argon plasma, the second phase of the proposed research project will be to obtain magnetoaerodynamic drag and shock stand-off distance data of an engineering nature using nitrogen and simulated air plasmas. No complications are expected as far as the thermophysical data are concerned because extensive tabular data of the properties of nitrogen and oxygen have been calculated.

It is hoped that this study will provide a better understanding of fundamental concepts as well as a better insight into the potentialities of various applications.

VI, 5 PRELIMINARY TESTS IN THE JPL LIQUID SODIUM TUNNEL

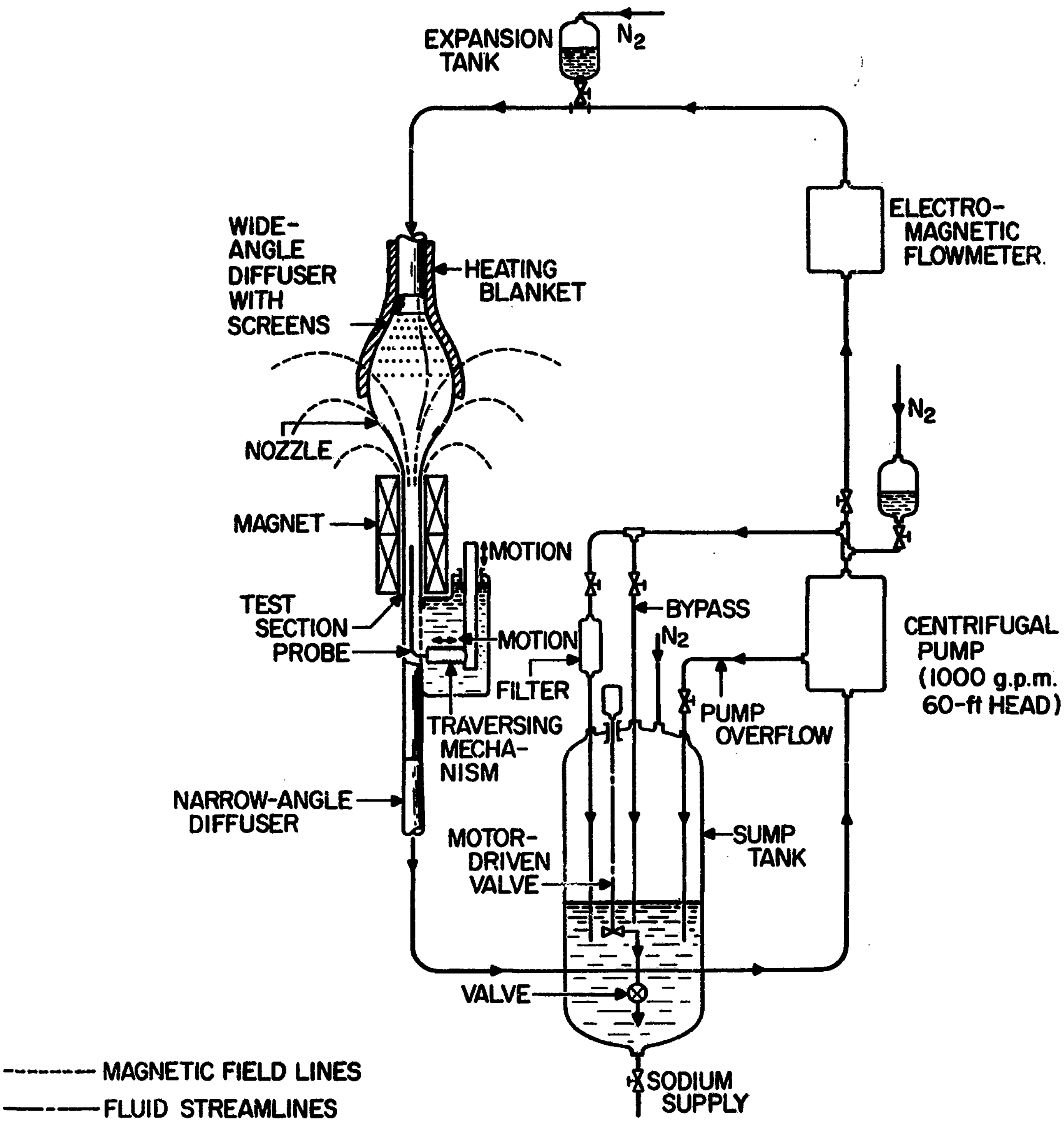
T. Maxworthy

Jet Propulsion Laboratory
Pasadena, California

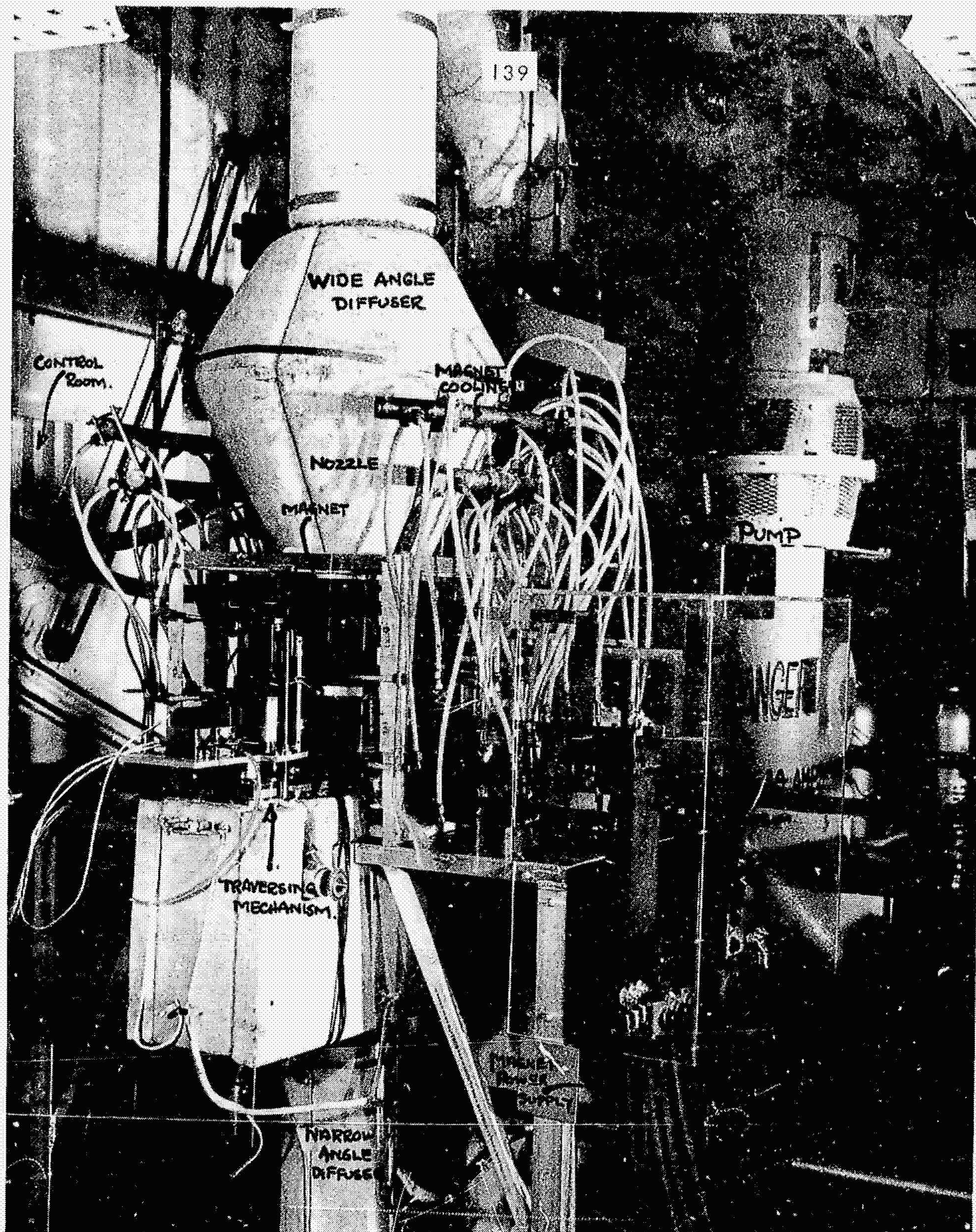
A liquid sodium tunnel has been designed and constructed to study magneto-fluid dynamic effects. It is described and the results of preliminary experiments presented.

Comparisons are made between total pressure, static pressure and velocity profiles in the test section with and without an applied magnetic field.

Significant differences are noted in the two situations and hypotheses are presented to account for them. The most profound effects seem to be caused by entry and exit phenomena, i.e., the interaction which occurs when the fluid flows into and out of the magnetic field region.



FLOW DIAGRAM FOR THE J.P.L. LIQUID SODIUM TEST FACILITY


WIDE ANGLE
DIFFUSER
CONTROL
ROOM.
MAGNET
COOLING
NOZZLE
MAGNET
PUMP
TRAVERSING
MECHANISM.
MAGNET
POWER
SUPPLY
NARROW
ANGLE
DIFFUSE

VII, 1

THEORETICAL CURRENT-VOLTAGE CURVE IN LOW-PRESSURE CESIUM DIODE FOR ION-RICH EMISSION

C. M. Goldstein
NASA Lewis Research Center
Cleveland, Ohio

Current-voltage characteristics for the two-species collisionless, infinite parallel-plate thermionic diode have been computed for ion rich emission. It is shown that over a wide range of α (ratio of ion to electron emission charge density) the two species total ion current characteristic differs appreciably from the single species characteristic based on Langmuir's solutions. In addition, it is shown that the net current characteristic is even more liable to misinterpretation due to the non-negligible electron current, even for large α .

VII, 2 THE EFFECTS OF ELECTRON HEATING AND ION SLIP ON THE PERFORMANCE OF AN MHD GENERATOR

F. A. Lyman
NASA Lewis Research Center
Cleveland, Ohio

The work described herein is the calculation of the effect of electron heating on the performance of a magnetohydrodynamic generator. The initial calculations dealt with argon seeded with small amounts of cesium. Two effects were of particular interest: first, the effect of varying the amount of seed, and second, the effect of varying the magnetic field and gas pressure.

The basic theory of non-thermal ionization at elevated electron temperatures was formulated by Kerrebrock, and the application of the theory to MHD generators was made by Hurwitz, Sutton, and Tamor, and by Wright and Swift-Hook. The present calculations depart from the above analyses in two respects. First of all, it was noted that electron-ion collisions may be the dominant process for energy exchange between the electrons and the heavier particles, and this fact was taken into account. Secondly, it was found that the electrons could attain sufficiently high energies to ionize the argon, in fact, the ion densities due to the cesium and the argon were found to be comparable at electron energies of less than one electron volt.

The inclusion of the two facts mentioned above in the theory led to an interesting result regarding the amount of seed required for maximum power. It was found that the highest power density was attained without seed.

Although ion slip has a deleterious effect on power generation for sufficiently high magnetic fields or sufficiently low gas pressures, this effect can be minimized by operating the generator at the proper pressure. Large magnetic fields require high operating pressures, but for the highest fields which are presently attainable the static pressures required to minimize ion slip are not unreasonable.

The above results were presented at the 4th Symposium on Engineering Aspects of Magnetohydrodynamics in April 1963 and are contained in a proposed technical note. The work is now being continued along the following line.

The previously mentioned theory is based on first order transport theory. Since it is known that the difference between first order and

second order transport coefficients is appreciable, the second order theory for a partially ionized gas developed by Burgers and Pipkin was applied to the electron heating problem. The results of the second order theory gave slightly more optimistic values for the power.

The work is now being extended in two directions. First, an attempt is currently being made to obtain a fairly rigorous second order transport theory which will include the effects of elevated electron temperatures and spatial nonuniformities. Second, the effect of inelastic collisions will be included within the framework of the simpler model.

VII, 3 MHD POWER GENERATION WITH NON-EQUILIBRIUM IONIZATION

L. D. Nichols
NASA Lewis Research Center
Cleveland, Ohio

MHD Generators are now being considered for use in space for at least two reasons (a) as an alternative method should turbines and other schemes fail to be developed, or (b) if the top temperature that can be achieved is limited by the turbine rather than by the reactor. At present it seems that the turboelectric systems will be lighter, barring some breakthrough in the design of MHD system components. However, if reactors can be developed to deliver gas at temperatures approaching 3000°F, then the turbine will possibly have to be replaced by an MHD Generator. Consequently, in the event that MHD would be chosen for either of the above reasons, its feasibility is being studied. The simplest scheme yet proposed in terms of system components is the single fluid generator whose electrical conductivity exceeds the equilibrium value by means of magnetic field ionization. Theoretical calculations for a linear, constant area Faraday generator operating as a part of a Brayton cycle have been made. Upon incorporating certain parameter optimizations, the calculated results show definite promise.

This type of generator will therefore be studied experimentally using Argon as the working fluid. The cycle will operate continuously with a maximum gas temperature of 4000°R, a maximum pressure of 5 atmospheres, a mass flow rate of 5 lb/sec with the fluid entering the constant area generator channel at Mach Number 3. Power output should be of the order of a few hundred kilowatts.

VII, 4

ROTATING MHD INDUCTION GENERATORS

R.E. Schwirian and E.J. Morgan
Case Institute of Technology
Cleveland, Ohio

NsG 198-62

Solutions have been obtained in the past for the following rotating induction generator problems:

1. Vortex generators without viscosity and assuming that the perturbations in the magnetic field are small (small magnetic Reynolds numbers) and that the perturbations in the fluid field are small. The electrical conductivity is assumed to be a simple scalar. Numerical solutions have been obtained for a number of values of the ratio of the inner radius to the outer radius, for several values of the length to radius ratio, and for one value of the slip. The effect of viscosity has also been examined.

2. Solid body rotation, again for small magnetic Reynolds numbers. Numerical solutions have been obtained for various values of the radius ratio and various values of the length to radius ratio.

More recently, a solution has been obtained for the infinitely long hollow cylinder for all magnetic Reynolds numbers. Computations for various radius ratios are now being completed.

In order to verify some of the above solutions, experimental measurements of torque and dissipation have been made on hollow and solid metal cylinders of various length to radius ratios placed in a rotating uniform magnetic field.

VII, 5 A MAGNETODYDRODYNAMIC ELECTRIC POWER GENERATOR USING SEEDED COMBUSTION PRODUCTS OF CYANOGEN AND OXYGEN

I. Fruchtman
NASA Langley Research Center
Langley, Virginia

In an effort to develop a small, lightweight and efficient electric power supply for possible moderate-time (several days) application in space missions, an analysis has been made and laboratory tests have been started for a constant Mach number MHD electric power generator. The working fluid of this generator is the combustion products of the cyanogen-oxygen flame seeded with cesium. The theoretical determination of generator efficiency and power output capability was made using a computer program involving the one-dimensional momentum and energy equations, following generally the work of Sherman but with some innovations to account grossly for the effects due to heat transfer and skin friction.

The results of the calculation are presented to show the influences on the generated power due to: (1) the magnetic field, (2) the Mach number, (3) the loading, and (4) the heat-transfer level. These results show that for both the heat transfer and the inviscid case, the maximum power is generated at $M = 0.9$. The results also show that for the case of no heat transfer and skin friction and with a magnetic field of 20,000 g, power of about 3.8 kw could be produced from a solid electrode generator 10 cm long whose channel area varies from 1 cm^2 at the inlet to 3 cm^2 at the outlet. However, when heat transfer and skin friction are considered (for a wall temperature of 1500°K) this same generator will only produce 1.4 kw. Increase of the wall temperature to 3000°K increases the generated power to 2.1 kw.

Using the results from this analysis a generator was designed and built, and tests have recently begun. Components of the generator, in addition to the generator section, includes combustion chamber, vacuum system, and a large iron-core, H-frame magnet capable of maintaining a field strength of up to 20,000 gauss.

Experimental results are presented to show the generated power as a function of resistive load, and as volt-current plots or load lines. Plots are given for various magnetic-field strengths and seeding percentages. Also presented are pressure distributions along the channel, and bulk plasma conductivity and collision frequency measurements. Means to improve the generator performance and directions for future efforts are discussed.

VII, 6

MHD A-C POWER GENERATION

H.H. Woodson
Massachusetts Institute of Technology
Cambridge, Massachusetts

NsG-368

This research program involves the theoretical and experimental study of two types of MHD a-c power generators that do not use capacitors or synchronous condensers to supply reactive power. As a result, these generators provide the possibility of generating a-c power directly by an MHD process without the crippling disadvantages imposed by a necessity to supply reactive power by conventional means.

One generator is a conduction type generator in which the gyrator effect is used to make one inductance tune another inductance. This end is accomplished by cross-coupling two conduction generators in an appropriate manner or by using the Hall effect.

Theoretical results obtained thus far show that both conduction generators should operate successfully when the basic machine is capable of operation as a self-excited d-c generator. Thus far the operating frequencies attainable with gas conditions that are typical for continuously operating machines are somewhat low. Work is underway to investigate different geometries and operating conditions that may enhance performance.

A second generator is the wave-type generator which uses magneto-acoustic waves to couple between fluid-flow power and electric power in a distributed electric circuit. This coupling is analogous to that which occurs in beam-type microwave tubes. Initial analyses that used a small-signal model with weak coupling between gas and circuit indicated machine sizes too large to be practical. More recent studies considering tighter coupling have shown that the machine size for successful operation may be reduced significantly.

Experiments on both machine types are being performed with modified homopolar configurations. These pulsed experiments use toroidal channels in which part of the channel is used as a driver and part as a test section. In both cases we have obtained essentially steady flow of gas with high enough conductivity and velocity over a long enough period of time to perform some preliminary experiments. The object in each case is to produce suitable conditions for studying the MHD interactions that will occur in the two types of generators cited above.

VIII, 1

EXPERIMENTAL PROBING OF PLASMAS WITH OPTICAL MASERS

A. A. Dougal
The University of Texas
Austin, Texas

Dispersion of coherent radiation from an infrared and optical maser beam strongly coupled to a plasma filled optical resonator was experimentally observed and readily permits time resolved, quantitative, measurement of plasma electron density. A fully ionized plasma is produced in hydrogenic gas at 100 microns pressure by a 50 megawatt super-high power radio frequency preheater.(1) A 1.5 MC, 1800 gauss peak, preheating B_z field induces a E_θ greater than 200 volts/cm in plasma partially ionized and immersed in a slowly rising reverse B_{zo} bias field. Complete ionization is effected within three microseconds. A specially designed continuous wave helium-neon optical maser delivers coherent infrared at 33,900 Å and coherent visible at 6328 Å in a single output beam from one end of the maser. The plasma tube with quartz windows is located between the optical maser and an external planar reflector forming a plasma filled resonator strongly coupled to the optical maser. A silicon wafer splits the output beam; the 33,900 Å radiation passes through the wafer into the plasma filled region; the 6328 Å radiation is reflected directly from the wafer into either a multiplier phototube or a photoconductive detector. Dispersion of the 33,900 Å radiation by the plasma electrons effects a frequency shift of the plasma filled resonator which is strongly coupled through the 33,900 Å beam to the optical maser. This coupling results in simultaneous amplitude modulation of the 33,900 Å and 6328 Å emission. The amplitude modulation of the 6328 Å is detected. The time variation of declining plasma electron density from 5×10^{15} per cm^3 at 5 microseconds over a period of 100 microseconds is experimentally observed. These experimental results confirm the analytical predictions by the author that appreciable dispersion of coherent infrared and visible radiation from optical masers which is interacted with plasmas would occur. (2,3,4,5)

(1) R. Z. Gribble and Arwin A. Dougal, "Experiments on Super-high Power Preheating of Hydrogen Plasmas", Bull. Am. Phys. Soc., 11-8, 131 (1963).

(2) Arwin A. Dougal, "Dispersion of Optical Maser Beams in Magnetoplasmas", Bull, Am. Phys. Soc., II-8, 163 (1963).
(3) Arwin A. Dougal, "Theory for Optical Maser Probing of Plasma-Filled Optical Resonator, "Bul. Am. Phys. Soc., II-8, 130-131 (1963).
(4) Arwin A. Dougal, "Optical Maser Probing Theory for Magnetoplasma Diagnostics", Proceedings of the Fourth Symposium on the Engineering Aspects of Magnetohydrodynamics, Institute of Electrical and Electronics Engineers, New York 21, New York, I-4 (1963).
(5) Arwin A. Dougal, "Theory for Optical Maser Diagnostics of Ionized Gases" submitted to the Proceedings of the VI th International Conference on Ionization Phenomena in Gases, Faculté des Sciences de Paris, Center d' Orsay, July 9, 1963.

VIII, 2 RATE OF ENERGY LOSS OF ENERGETIC ELECTRONS IN A PLASMA:

I THEORETICAL

M.R. Smith and W.B. Johnson
Case Institute of Technology
Cleveland, Ohio

NsG 198-62

Theoretical values of the rate of energy loss of energetic electrons passing through a plasma have been computed. The model used was that corresponding to an electron-electron collision with a suitable adjustment of the maximum cutoff distance to account for collective effects. The cross-section employed was the Mott scattering relation so as to include the contribution due to the indistinguishability of the electrons. Appropriate averages of this cross-section over the plasma electron velocity distribution were made so as to account for the skewed Maxwellian distribution caused by a moving plasma. This was done to estimate the effects of a plasma formed by a strong shock wave such as would be expected in the experiment described in the following paper. For typical plasma parameters ($T \sim 30{,}000^{\circ}k$ and $n_e \sim 5 \times 10^{16}$ electrons/cm^3) the rate of energy loss was computed to be approximately 90 volts/cm. Calculations excluding the effects of collective oscillation excitation characterized by the maximum cutoff parameter taken to be the Debye length yield energy losses lower than the above by almost one order of magnitude. Thus it is seen that the excitation of plasma oscillations is the dominant mechanism for the loss of energy by electrons traversing a plasma.

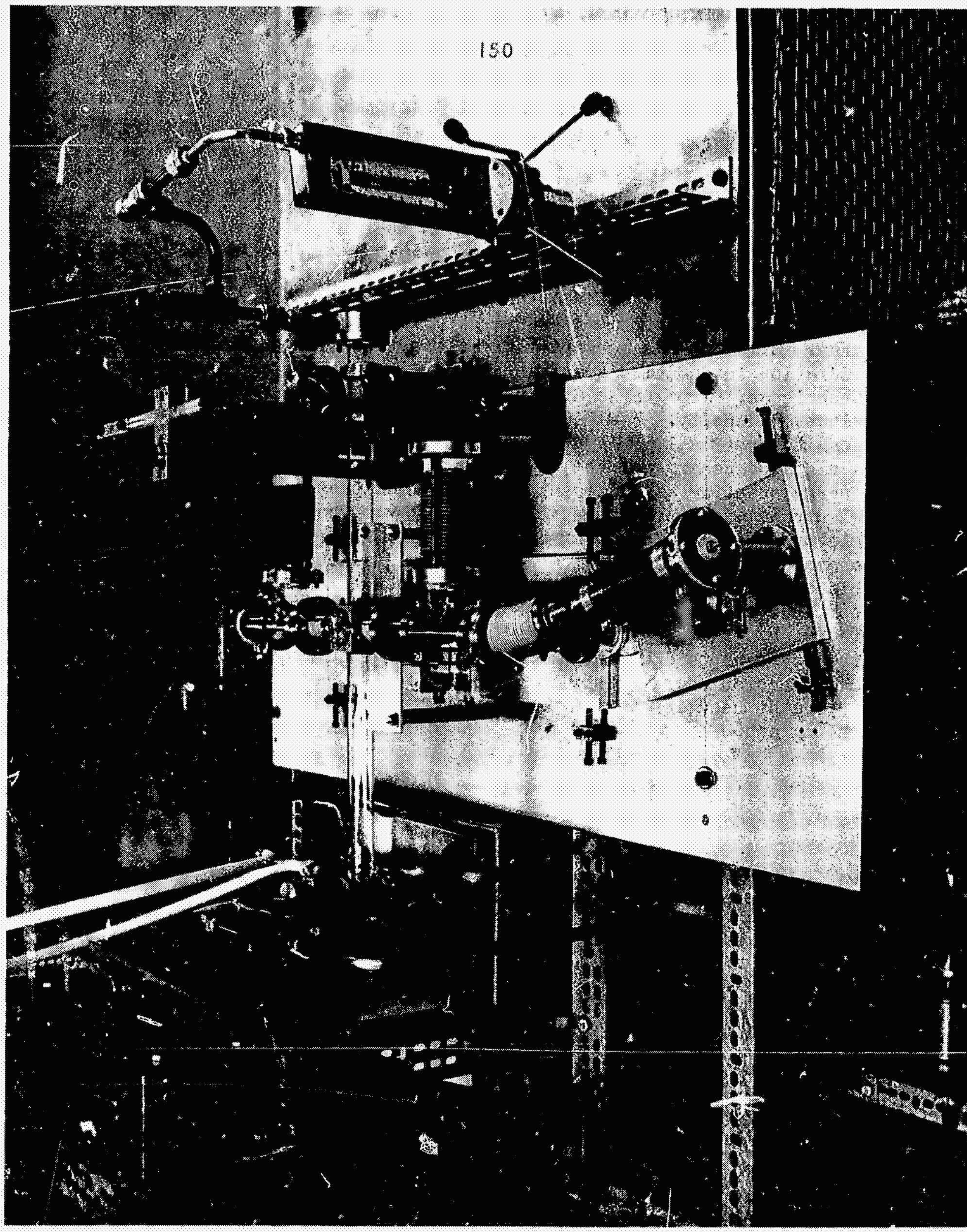
VIII, 3 RATE OF ENERGY LOSS OF ENERGETIC ELECTRONS IN A PLASMA:

II EXPERIMENTAL

W.B. Johnson and M.R. Smith
Case Institute of Technology
Cleveland, Ohio

NsG 198-62

An experiment is being performed to measure the rate of energy loss of high energy electrons upon traversal of a plasma. Mono-energetic electrons with an energy of 3500 volts are incident upon a high temperature plasma produced by a linear electromagnetic shock tube. Simultaneous measurements of absolute line and continuum radiation intensities are taken using time resolved spectroscopic techniques. From these are infered the plasma temperature and electron density. Typical values for the temperature and electron density are 3×10^{4}°k and 5×10^{16}electrons/cm^3, respectively. During a single discharge of the capacitor bank four complete scans of the energy spectrum at different electron densities of the transmitted electrons are accomplished electronically. The number of transmitted electrons as a function of energy for all four scans is displayed on a single oscilloscope. Energy selection is accomplished by using a biased Faraday cup detector. Data from these experiments will be compared with the theory given in the previous paper and to other theories. The data obtained will also give information regarding the approach to equilibrium of a group of electrons initially having a S-function energy distribution. Initial data will be presented. Apparatus used in these experiments is shown in the accompanying photograph.



VIII, 4

PLASMA FLUX MEASUREMENT

D.N. Bowditch
NASA Lewis Research Center
Cleveland, Ohio

One of the important quantities in plasma source or thrustor operation is the total plasma or ion flux expelled. The plasmas, studied by our group at the Lewis Research Center generally have number densities of about 10" particles per c.c., and electron temperatures of 10 volts or more, making sheath thicknesses less than one millimeter. Therefore, it is impossible to penetrate the plasma with an electric field which would separate the ion and electron currents so that one must collect the ions at the edges while reflecting the electrons.

To keep the measurement from disturbing the plasma, an electron current equal to the ion current must be collected. If high energy electrons are reflected at the ion collecting surface, and low energy electrons collected, then a net power is added to the electron gas, which increases the ionization. This power can be kept negligibly small by segmenting the ion collector to minimize current, and by suitable choice of an electron collector.

For accurate measurement, there must also be negligible recombination and a predictable amount of secondary electron current. For atomic plasmas, it appears, from the theory of reference 1, that little recombination should take place over a distance of 10 cm for densities as high as 10^{14} particles per c.c. and electron temperature of one e.v. or more. Hagstrum (reference 2) has shown that Auger ejection is the method of secondary electron production for noble gas ion bombardment. He has found that over a range of 10 ev to 1000 ev, there is a fairly constant secondary emission coefficient for the noble gases on tungsten and molybdenum. Therefore the secondary electron current can be predicted for collectors on the wall or in a thrustor exhaust.

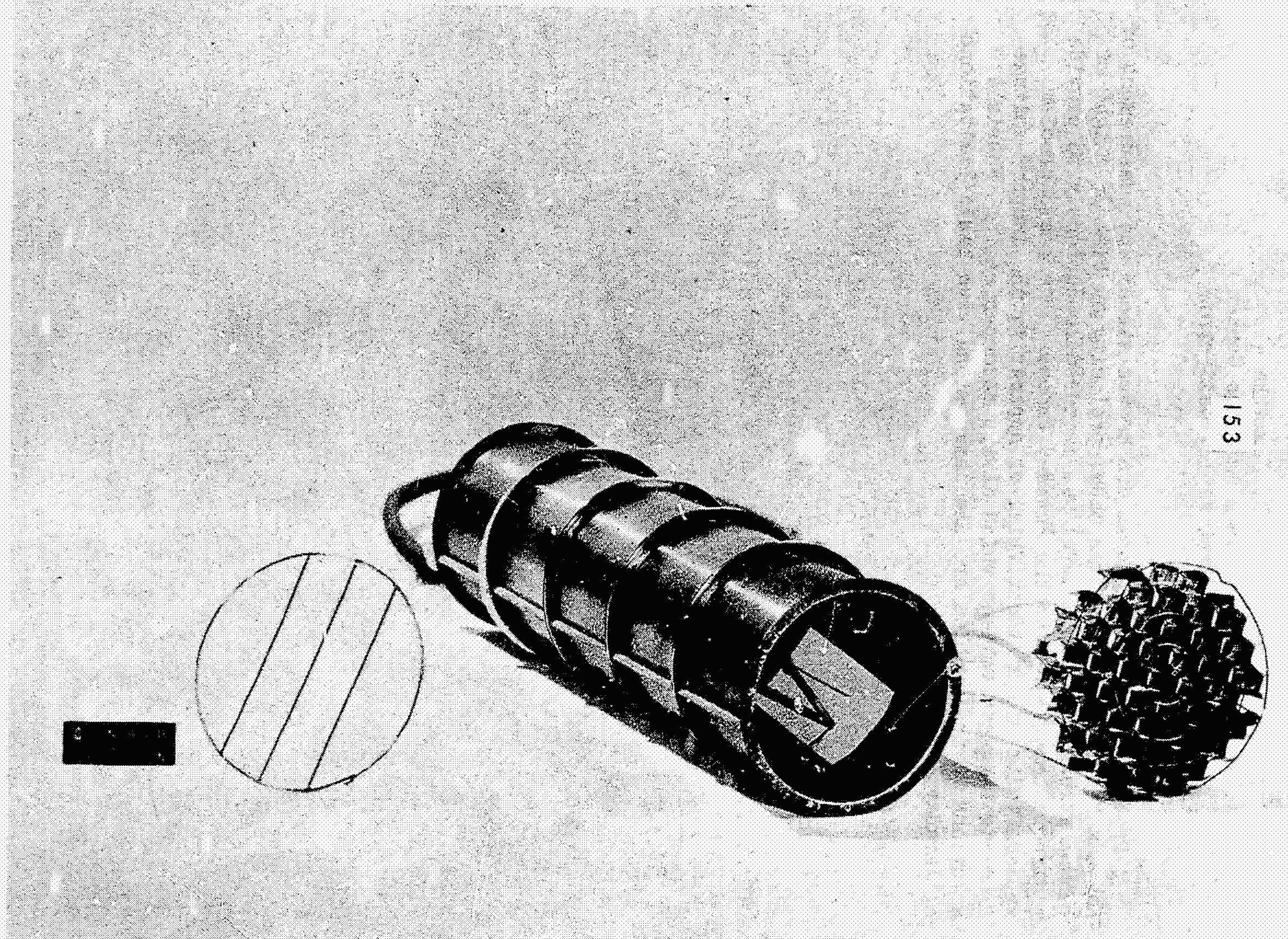
A program has been underway at the Lewis Research Center to determine if flux measurements can be made without significantly distorting the plasma. Configurations under investigation are segmented conducting walls downstream of the exit, low solidity screens across the exit, a honeycomb ion collector across the exit, and small flat probes, perpedicular to the flow, that are large with respect to the Debye length and small with respect to the mean free path. The idea in all cases is to place an electron reflecting sheath in the path of the ion current. These probes are being investigated downstream of a P.I.G. type discharge in Argon, whose characteristics are described in reference 3. The plasma properties are measured by interpreting

the electron saturation region of a Langmuir probe 0.001" in diameter, and 0.2" long. The electron current is more isotropic than the ion current in the type of plasma investigated, and the small probe size limits the electron saturation current to at most a few milliamps in a 1-3 amp discharge. It has been determined that the ion flux can be measured using conducting walls with no appreciable energy addition to the plasma. This can be done by segmenting the walls, and biasing two segments so that the segment with a slightly higher floating potential collects ions, and the other segment collects an equal electron current. The other probes are still being investigated.

Reference:

1. Hinnov, Einar, and Hirschberg, J.: Electron-Ion Recombination in Dense Plasmas. Phys. Rev. Vol. 125 No. 3, p. 795 (1962).(Feb. 1, 1963).
2. Hagstrum, H.D.: Auger Ejection of Electrons From Tungsten by Noble Gas Ions. Phys. Rev., Vol. 96, No. 2 p. 325 (1954) (Oct. 15, 1954).
3. Domitz, Stanley: Experimental Evaluation of a Direct-Current Low-Pressure Plasma Source. NASA TN D-1659, 1963.

TOTAL PLASMA FLUX PROBES



VIII, 5 MEASUREMENT OF STREAM VELOCITY WITH FARADAY PROBES

J.R. Jedlicka
NASA Ames Research Center
Moffett Field, California

Probes were inserted in an arc heated stream and measurement of the u x B induced voltage was made. Velocity by time of flight of random stream ionization level was measured concurrently to provide a direct comparison with the Faraday Probes. The basic problem appears to be one of identifying or separating the induced voltage from the Langmuir voltage which always accompanies it. Possible solutions to the problem are discussed along with basic limitations of Faraday Probes.

VIII, 6 AN RF PROBE SYSTEM TO MEASURE THE CONDUCTIVITY AND VELOCITY OF PLASMAS

V.J. Rossow
NASA Ames Research Center
Moffett Field, California

Some results will be presented of a study made on a system of small coils designed to measure the electrical conductivity and velocity of the plasma stream produced by the constricted-arc jet wind tunnel of the Magnetoplasmadynamics Branch at Ames. One probe is excited with RF power and the other probes measure the impressed field as modified by the streaming fluid. A theoretical study of the magnetofluiddynamic interaction relates the magnitude of the measured fields to the conductivity and velocity of the plasma.